A STREAMLINE MODEL FOR THE WATERFLOOD OF NAVAL PETROLEUM RESERVE NUMBER THREE

Kenneth E. Goltz

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APPROVED:

A STREAMLINE MODEL FOR THE WATERFLOOD OF NAVAL PETROLEUM RESERVE NUMBER THREE

by

KENNETH E. GOLTZ, B. Ch. E.

THESIS

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Kenneth E. Goltz
Lieutenant
Civil Engineer Corps
United States Navy

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Austin, Texas

ABSTRACT

A waterflood of the Second Wall Creek Sand of Naval Petroleum Reserve No. 3 is being considered in order to increase the ultimate oil production. A streamline model of the Second Wall Creek Sand was developed here and used to predict the response of the reservoir to a waterflood.

Results of the model study indicate that the oil production of the Second Wall Creek Sand can be increased by as much as 15,000,000 barrels over a twelve year period by waterflooding. This would bring the total production available from the Second Wall Creek Sand to around 32,000,000 barrels.

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CHAPTER I

INTRODUCTION

Naval Petroleum Reserve No. 3 is located in Natrona County, about thirty-five miles north of Casper, Wyoming. The major geological structure on the reserve is an anticline called "Teapot Dome". The Second Wall Creek Sand is the most important of the several oil bearing formations on the anticline.

The Second Wall Creek Sand is a solution gas drive reservoir. There appears to be very little natural water drive. Early estimates, based on recovering one-seventh of the original oil in place, predicted the recoverable reserves from this formation to be around 17,000,000 barrels(1).

Waterfloods of the same formation in neighboring fields have proven to be successful in increasing production. Therefore, in order to enhance the recovery, the development and production of the Second Wall Creek Sand as a waterflood is being considered.

The objective of this work is to apply streamline simulator techniques to the Second Wall Creek Sand and predict the results of a waterflood under certain operating conditions.

CHAPTER II

THE STREAMLINE MODEL

The theory and development of the streamline model have been rigorously described by LeBlanc and Caudle(2), Rust(3), Wessels(4) and Kazmann(5). A review of the assumptions and the mathematics is presented here.

2.1 Basic Assumptions

The basic assumptions used in formulating the streamline model are as follows:

1. Negligible gravitational effects within the reservoir. There is no gravity segregation of fluids.
2. Steady-state flow within the reservoir. Incompressible reservoir fluids. Operations are at nearly constant pressure.
3. Homogeneous, isotropic reservoir.
4. Uniform dispersion of free gas.
5. Oilbank formation.

The simulator used is designed specifically for oil bank build-up and will not accurately predict the results of other operations such as pressure maintenance.

2.2 Fundamental Equations

The starting point for the development of the streamline model is the continuity equation. This partial differential equation is derived from a three dimensional material balance and is written as:

$$\frac{\partial\left(\rho u_x\right)}{\partial x} + \frac{\partial\left(\rho u_y\right)}{\partial y} + \frac{\partial\left(\rho u_z\right)}{\partial z} = \phi \frac{\partial \rho}{\partial t} \tag{2.2.1}$$

The volumetric flux may be expressed by Darcy's Law in the differential form as:

$$u = \frac{q}{A} = - \frac{k}{\mu} \frac{d\Phi}{dl} \tag{2.2.2}$$

When the volumetric flux components in the x, y and z directions, as described by Darcy's Law, Equation 2.2.2, are substituted into Equation 2.2.1, the following equation results:

$$\frac{\partial}{\partial x}\left(\frac{\rho k_x}{\mu}\frac{\partial\Phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\rho k_y}{\mu}\frac{\partial\Phi}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{\rho k_z}{\mu}\frac{\partial\Phi}{\partial z}\right) = \phi\frac{\partial\rho}{\partial t} \tag{2.2.3}$$

By using the assumptions listed previously, Equation 2.2.3 may be simplified. The resulting equation may be written in the form of a La Place equation.

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} = 0 \tag{2.2.4}$$

The solution of Equation 2.2.4 yields the pressure at any point in a porous medium for which the assumptions made are valid. Knowing the pressure at all points in a porous medium, the average velocity of a fluid particle, and thus its movement, may be computed.

By transforming to cylindrical coordinates and allowing radial flow about a point, Equation 2.2.4 may be solved for the flow potential in a horizontal, isotropic, homogeneous porous medium. Restoring the resulting equation to rectangular coordinates and using the rule of superposition for a multi-well system, the solution of Equation 2.2.4 becomes

$$p(x, y) = p_m - \frac{\mu}{4\pi kh} \sum_{i=1}^{n} q_i \ln \left[\left(x-x_i\right)^2 + \left(y-y_i\right)^2 \right] \qquad (2.2.5)$$

where p_m is the mean reservoir pressure.

In a porous medium, the relationship of flux to velocity is

$$v = \frac{u}{\phi} = - \frac{k}{\phi\mu} \frac{dp}{dl} \qquad (2.2.6)$$

By differentiating Equation 2.2.5 with respect to x and substituting the resulting derivative into Equation 2.2.6 the velocity in the x direction in a rectangular coordinate system becomes:

$$v_x(x, y) = - \frac{1}{2\pi\phi h} \sum_{i=1}^{n} q_i \frac{x - x_i}{\left(x-x_i\right)^2 + \left(y-y_i\right)^2} \qquad (2.2.7)$$

In a similar manner, the velocity in the y direction becomes:

$$v_y(x, y) = -\frac{1}{2\pi\phi h} \sum_{i=1}^{n} q_i \frac{y - y_i}{\left(x - x_i\right)^2 + \left(y - y_i\right)^2} \qquad (2.2.8)$$

Using vector addition, the velocity of a particle of fluid is:

$$v = \sqrt{v_x^{\,2} + v_y^{\,2}} \qquad (2.2.9)$$

2.3 Finite Difference Equations for Movement

In order to apply Equations 2.2.7 and 2.2.8 to the streamline model, it is assumed that the velocity remains constant during any one small distance increment, Δs. Then the time increment, Δt, is calculated by:

$$\Delta t = \frac{\Delta s}{v} \qquad (2.3.1)$$

From the particle's starting point (x_s, y_s), it will move to a new point calculated as follows:

$$\begin{aligned} x_{s+1} &= x_s + v_x (x_s, y_s)\Delta t \\ y_{s+1} &= y_s + v_y (x_s, y_s)\Delta t \end{aligned} \qquad (2.3.2)$$

By starting on the wellbore of an injection well and successively applying Equations 2.2.7 through 2.3.2, a trace of any particle's movement may be made. This trace, called a streamline, is followed until it reaches a production well whereupon it is terminated. The travel time for a single streamline is the summation of the time increments

corresponding to the number of steps taken along the streamline.

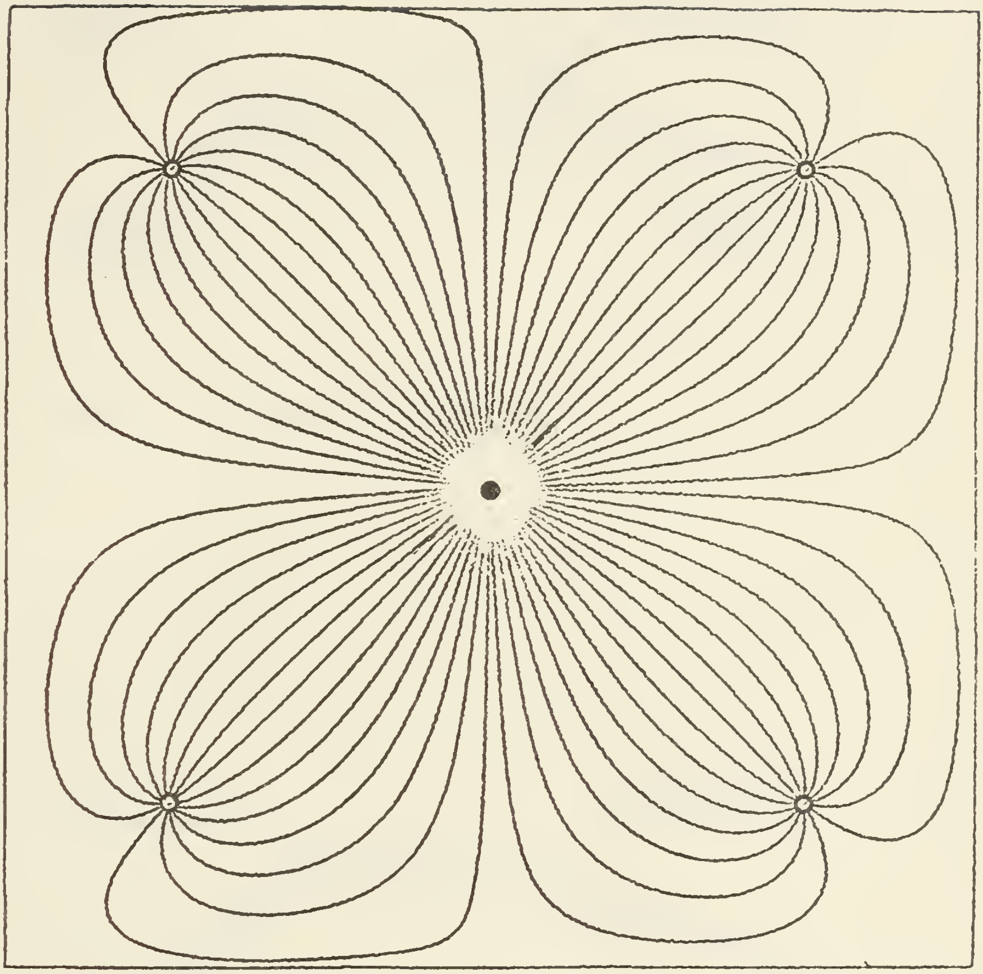
2.4 Streamtube Concept

In actual computation, a representative number of streamlines are chosen to represent all fluids emanating from the source. An example of the streamlines for a bounded pattern are shown in Figure 1. A few typical streamlines are shown in Figure 2. By dividing the distance between two adjacent streamlines into two equal parts, the streamline may be said to represent the flow of all the particles within the dividing lines. A streamtube has thus been described and is shown in Figure 3(3). As a fluid particle is traced along its streamline, the volume of fluid produced at the streamline's production well can be calculated and accumulated.

2.5 Multiple Fluid Flow

The streamline model described so far deals with a single fluid. In a waterflood operation, water is injected into the reservoir to displace the oil and gas. Therefore as many as three fluid regions may be present in the reservoir at any time and may each have a different mobility.

The first assumption for the multiple fluid system is that the oil is miscibly displaced by the water in a piston-like manner. The oil is banked up ahead of the water such that all oil displacement takes place at the leading edge of the water front. A diagram of the concentrations is shown on page 9.



● Injection Well
○ Production Well

Figure 1 Streamlines for a Bounded Pattern.

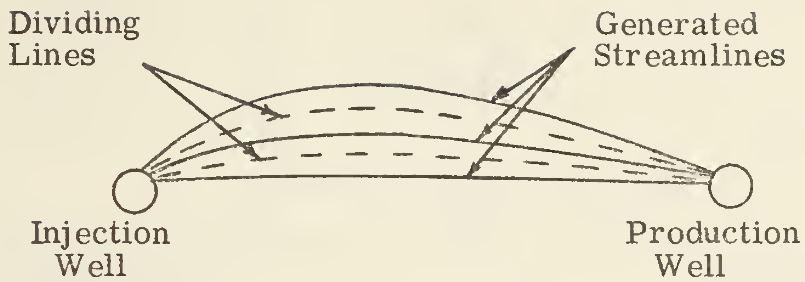


Figure 2 Typical Streamlines.

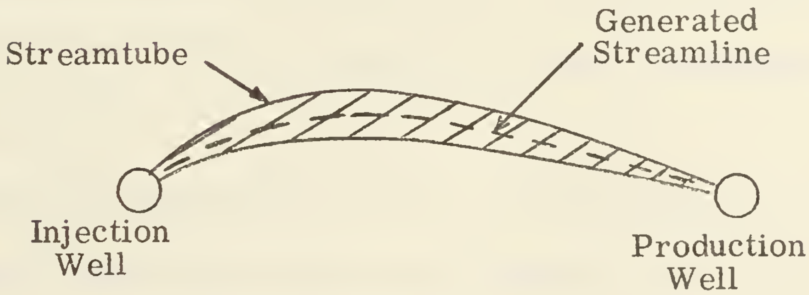
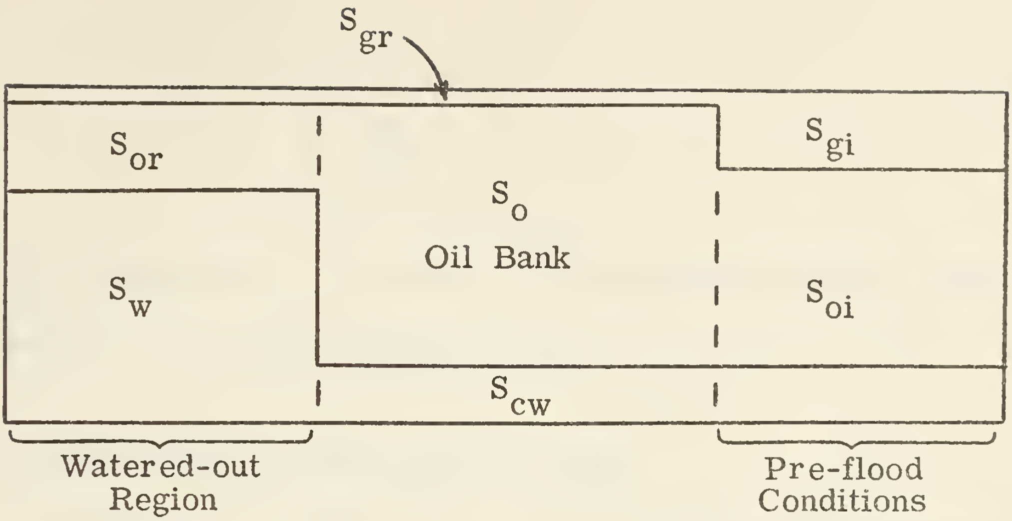


Figure 3 Typical Streamtube.



With the assumption of piston-like displacement the displacing fluid interface can be easily followed along the center pathline of a streamtube.

The most significant approximation used in extending the streamline model for multiple fluids is that the pathlines will be the same as the streamlines generated for a single fluid. This approximation, while not correct, has been found to be reasonable except at extreme values of mobility ratio(3).

As the fluids proceed along the streamtube the flow rate of the fluid stream will change because of the different fluid region mobilities. To correct for the changing fluid flow rate the concept of conductivity ratio is applied. Conductivity and conductivity ratio are developed and explained by Caudle(6). Briefly the conductivity ratio is a comparison of the conductivity of the medium at some time when more than one fluid is flowing to the conductivity of the medium initially when only one fluid was present. The general equation for the conductivity ratio is

$$\gamma = \frac{(p_i - p_o)}{\lambda_1 \sum_{k=1}^{\ell} \frac{\Delta p_k}{\lambda_k}} \qquad (2.5.1)$$

The velocity Equations 2.2.7 and 2.2.8 are multiplied by the conductivity ratio to correct for multiphase flow.

2.6 Modification for Thickness Variation

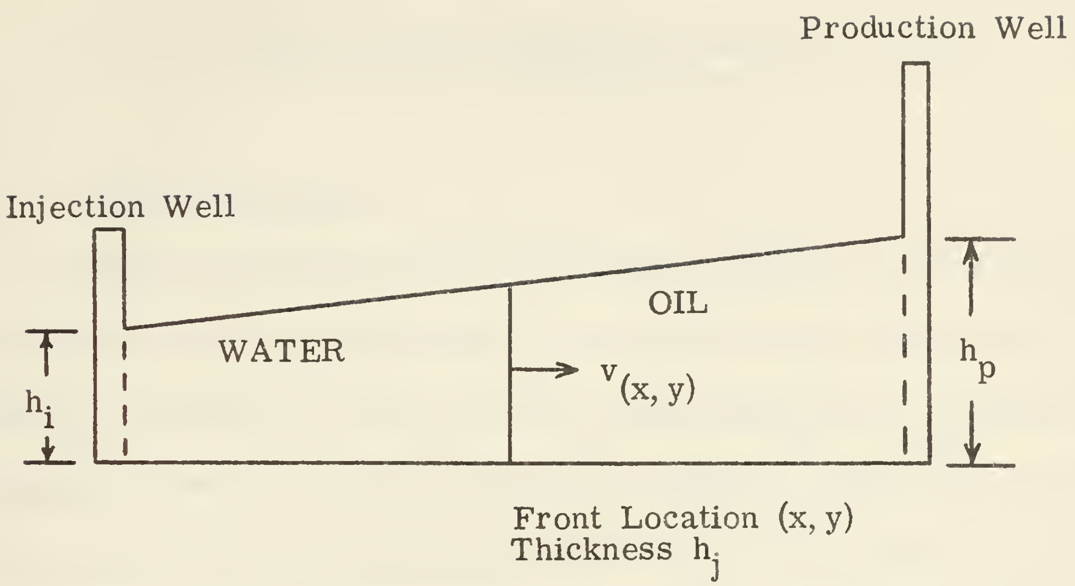
An empirical modification to allow for varying thickness has been developed by Wessels (4). This modification is useful if the thickness at each point in the reservoir can be defined. A system of grid squares with assigned thicknesses is used to describe the reservoir thickness variation.

The modifications for thickness variation are as follows:

$$v_x = -\frac{1}{2\pi\phi} \sum_{i=1}^{n} \frac{q_i}{h_i} \left[\frac{x - x_i}{(x-x_i)^2 + (y-y_i)^2} \right] \gamma \left(\frac{h_p}{h_j} \right) \qquad (2.6.2)$$

$$v_y = -\frac{1}{2\pi\phi} \sum_{i=1}^{n} \frac{q_i}{h_i} \left[\frac{y - y_i}{(x-x_i)^2 + (y-y_i)^2} \right] \gamma \left(\frac{h_p}{h_j} \right) \qquad (2.6.3)$$

The factor (h_p/h_j) is an approximation factor which reflects an increasing velocity as the thickness decreases and a decreasing velocity as the thickness increases. The diagram below shows the relationship between reservoir thickness and velocity for a single streamline.



2.7 Mathematical Bounding of the Streamline Model

An imaging technique developed by Lin (7) which can determine the necessary rates for a preselected set of image wells that will confine a system of streamlines within a given area was used for this study. The technique uses a least squares method to determine the image well flow rates so that a no-flow boundary is established between each of the reservoir bounding points.

CHAPTER III

APPLICATION OF THE STREAMLINE MODEL TO THE SECOND WALL CREEK SAND

3.1 Reservoir History

President Wilson's Executive Order of April 30, 1915 designated the Teapot Dome area in Wyoming as Naval Petroleum Reserve No. 3 (NPR 3). On April 7, 1922, the reserve was leased to the Mammoth Oil Company for the purpose of exploitation. Following a decision of the U.S. Supreme Court all of the producing wells on the reserve were shut-in on December 31, 1927. The field remained shut-in until 1951-1953 when an exploratory program was initiated; thereafter it was shut-in until 1958 when an offset drilling program was instituted to protect against drainage by adjacent operators.

The wells are distributed unevenly in the Second Wall Creek Sand because development was started at the north end of the reserve and was stopped prior to completion. Based on approximate surface area the northern third of the reserve has 69 wells, the middle third has 23 wells and the southern third has 13 wells.

Approximately 3,600,000 barrels of oil were produced prior to December 31, 1927. 1,200,000 barrels of oil have been produced since 1951 with most of this production occuring after 1958.

3.2 Location of Oil and Gas

Figure 4 shows the approximate locations of the gas cap, oil zone and water in the Second Wall Creek Sand(8).

The Second Wall Creek Sand just beyond the northwestern boundary of NPR 3 has been under waterflood for several years. The Navy has been producing wells along this boundary to protect against drainage. Consequently a portion of the Naval Reserve has been swept by the waterflood. To allow for this production, 170 acres along the northwestern boundary were omitted from the area which was modeled. The total area modeled was 3000 acres.

3.3 Reservoir Properties

Reservoir data and operating conditions were obtained from Tesoro Petroleum Corporation and U. S. Navy drawings of NPR 3 (8, 10, 11), Geological Survey and U. S. Navy publications (1, 9), U. S. Navy correspondence (12, 13) and various core data and logs provided by the Officer in Charge of Naval Petroleum Reserve No. 3.

Table I lists the reservoir and fluid properties used for the modeling study. A discussion of significant individual items follows.

<u>Porosity and Saturations</u> The average porosity and connate water saturation used are the same as those used in previous estimates of waterflooding at the north end of the reservoir (12, 13). No significant difference was noted between these figures and the core data examined.

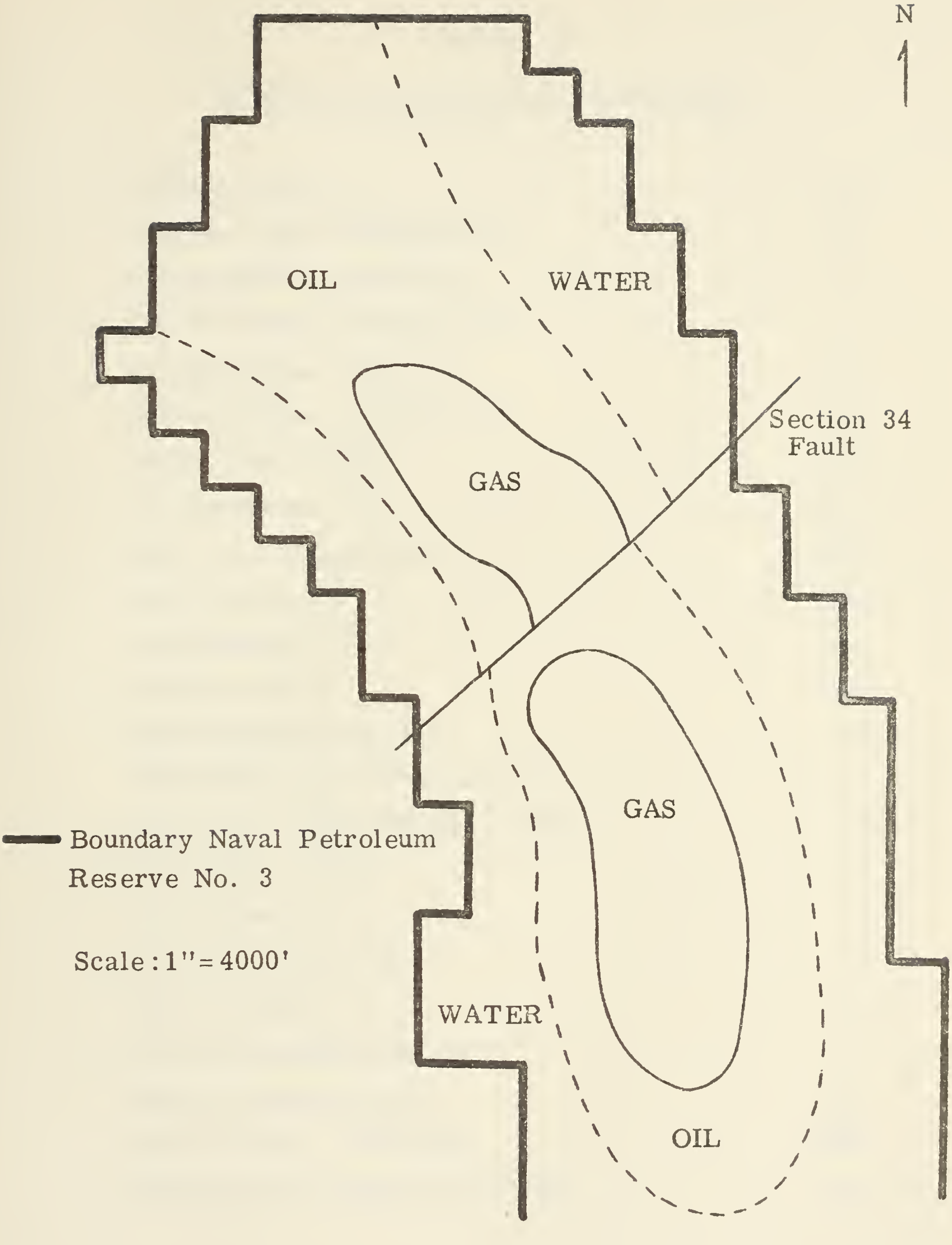


Figure 4 Location of Oil and Gas in the Second Wall Creek Sand.

TABLE I

RESERVOIR AND FLUID PROPERTIES

Porosity (Avg), %	17.5
Connate Water Saturation, %	35
Gas Saturation, Initial, %	5
Gas Saturation, Residual, %	0
Oil Saturation, Initial, %	60
Oil Saturation, Residual, %	20
Major Fault Blocks	10
Net Thickness, Ft.	21-60
Reservoir Area, Acres	3000
Depth (Avg), Ft.	2800
Temperature, ^{o}F	140
Pressure, PSI	1100
Permeability (Avg), MD	10
Formation Volume Factor, Oil	1.2
Formation Volume Factor, Water	1.0
Oil Gravity, ^{o}API	38
Oil Viscosity, CP	6
Water Viscosity, CP	.7
Gas Viscosity, CP	.12
Water/Oil Mobility Ratio	4
Gas/Oil Mobility Ratio	65
Gas Oil Ratio, SCF/BBL	1000
Solution Gas Oil Ratio, SCF/BBL	50

For this study it was assumed that the waterflood would start at the very beginning of the production. The model was run with an initial gas saturation of 5% to allow oil bank build-up to occur and to show the effect of fill-up time. The initial oil saturation used was 60%.

The residual gas saturation was set at zero because it was assumed that all of the free gas would either be displaced or put back into solution as the oil bank passed.

The residual oil saturation after the waterflood passed was set at 20%. This is almost twice the 12% average residual oil saturation found in the cores available. The residual oil saturation in the cores was considered an absolute minimum which would be difficult to achieve in the reservoir.

Fault Blocks The Second Wall Creek Sand is heavily faulted and was, for the presentation of well productivity data, divided into about twenty possible fault blocks(12). In order to model the field, taking into account the faulting, the field was divided into ten sections along the largest faults. It was assumed that the faults were sealed and the sections were then modeled independently. This had the added advantage of making the modeled reservoirs smaller and easier to manage. Also, properties which vary within the reservoir could be easily changed from section to section. Figure 5 shows the configuration of the ten fault blocks chosen.

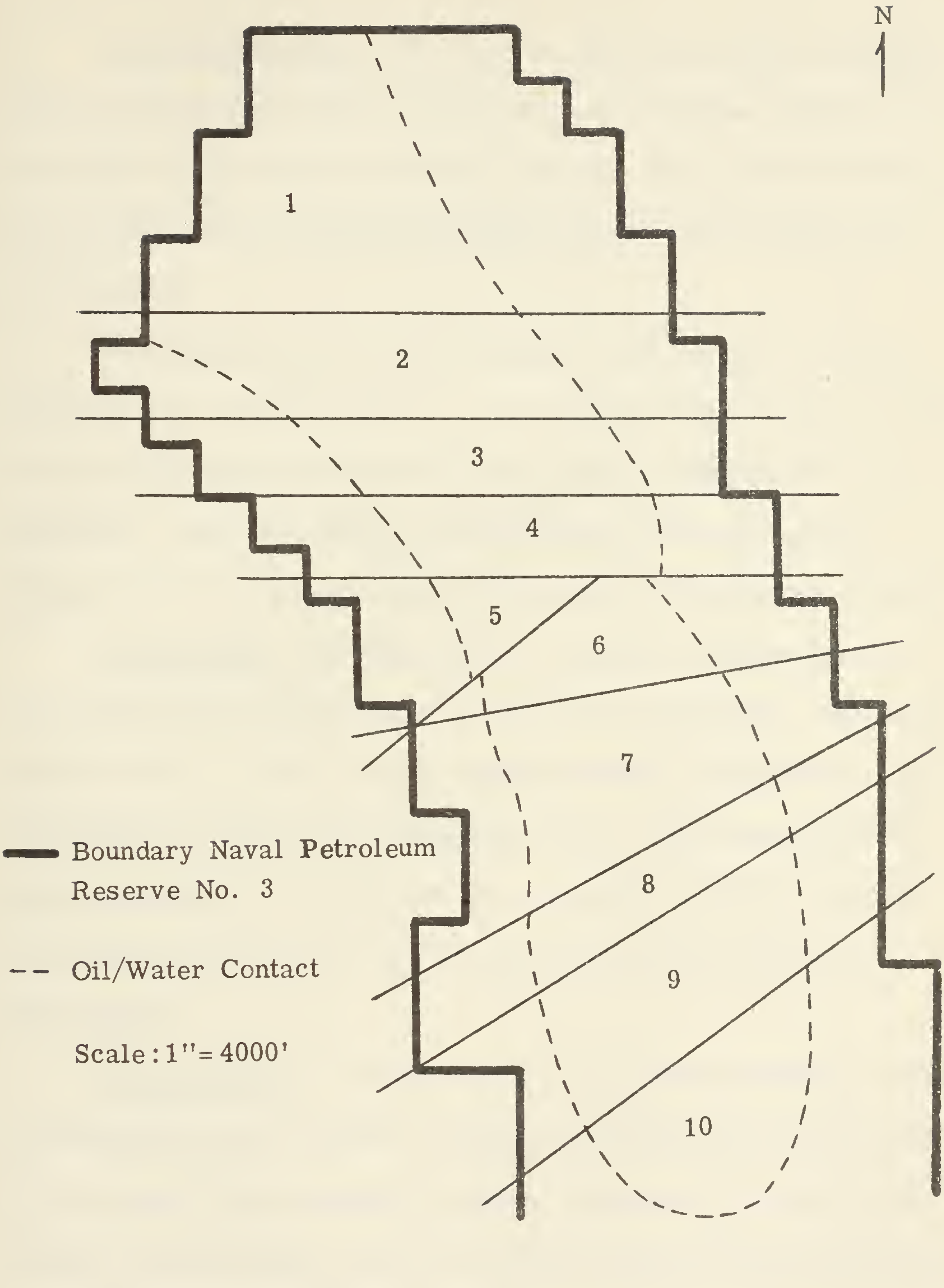


Figure 5 Fault Blocks Used in Modeling the Second Wall Creek Sand.

Net Sand Thickness Thin beds of shale are common throughout the Second Wall Creek Sand, but they thicken toward the south and east and split the sand into several distinct layers. Some wells have three or more layers of sand separated by shale beds from two to twenty-five feet thick(12).

Combining the information available from the cores with the general trends mentioned above, a percentage discount factor was used for each fault block to reduce the gross sand thickness to a net sand thickness. Table II shows the discount factors that were applied. Figure 6 shows the gross thickness of the Second Wall Creek Sand(10).

Permeability The temperature, pressure and permeability were used to determine the fluid and fluid flow properties. The permeability itself is not used in the streamline model calculations because the calculations are made at a constant flow rate. This means that the injection pressure will have to be great enough to make the injectors flow at the required rate. Rate selection will be discussed in the next chapter.

Gas-Oil Ratios Gas-oil ratios vary greatly depending on where in the field the well is located. The gas-oil ratio and solution gas-oil ratio are used by the computer program to indicate the arrival of the oil bank. Representative values of the two ratios were used but they do not represent a rigid material balance.

TABLE II

DISCOUNT FACTORS APPLIED TO
GROSS SAND THICKNESS
TO OBTAIN NET SAND
THICKNESS

Fault Block	Factor
1	0.8
2	0.7
3	0.7
4	0.8
5	1.0
6	1.0
7	0.8
8	0.7
9	0.66
10	0.66

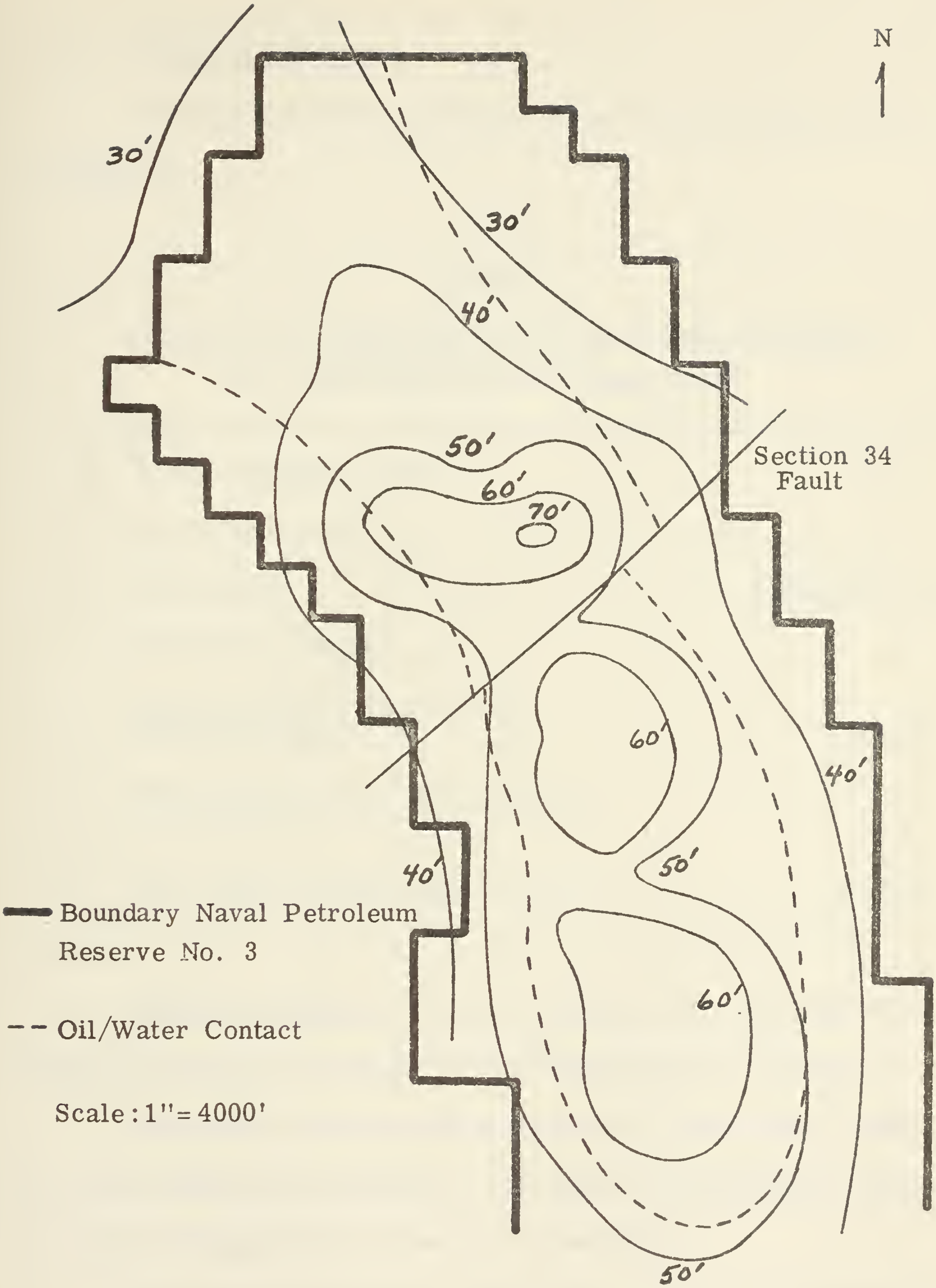


Figure 6 Isopachous Map of the Second Wall Creek Sand - Gross Sand Thickness.

3.4 Operating Conditions

Table III is a listing of the operating conditions used for the simulation.

TABLE III

OPERATING CONDITIONS FOR THE WATERFLOODING OF THE SECOND WALL CREEK SAND

No. of Production Wells	135
No. of Injection Wells	132
Well Pattern	5-Spot/Line Drive
Well Spacing, Acres	10
Maximum Oil Production Rate, STB/Well/Day	46-300
Oil Production Rates During Fill Up, STB/Well/Day	3-25
Total Water Injection Rate, STB/Day	23,000

Field Development Based on a proposed Navy Development Plan(11) the field was assumed to be drilled on ten acre spacing.

Well water injectivity was assumed to be in the same range as the well's initial oil productivity. Therefore, approximately a one-to-one ratio of injectors to producers was maintained.

The injection-production well pattern used was a combination five-spot and line drive. The injection wells were generally placed

along the outside, nearest the oil/water contact, in a line drive pattern to force the oil toward the center. Then, where area allowed, injection wells were placed within the producers in a five-spot pattern.

Production Well Rates In the streamline model the oil production rate of a well during the fill-up time is set equal to the present rate to which the well's oil production has declined. After oil bank breakthrough the oil production rate of a well is set equal to the initial or maximum oil rate of that well.

The initial rates for each production well were determined from a composite drawing of the Second Wall Creek Sand production(8). Since the reservoir will be waterflooded from the start, the oil rates during fill-up were set at 10% of each well's initial rate. At reservoir conditions, the total water injection rate was set equal to the total oil production rate after fill-up to satisfy the steady state assumption.

The individual injection rates were assigned to the injection wells in such a manner to contain the streamlines as much as possible to the oil bearing area. Some flow into the gas cap and the watertable cannot be stopped but proper balancing minimized the losses.

Figures 7 and 8 show the well pattern used and the streamlines generated by the model reservoir. See Appendix A for a listing of the individual well data used.

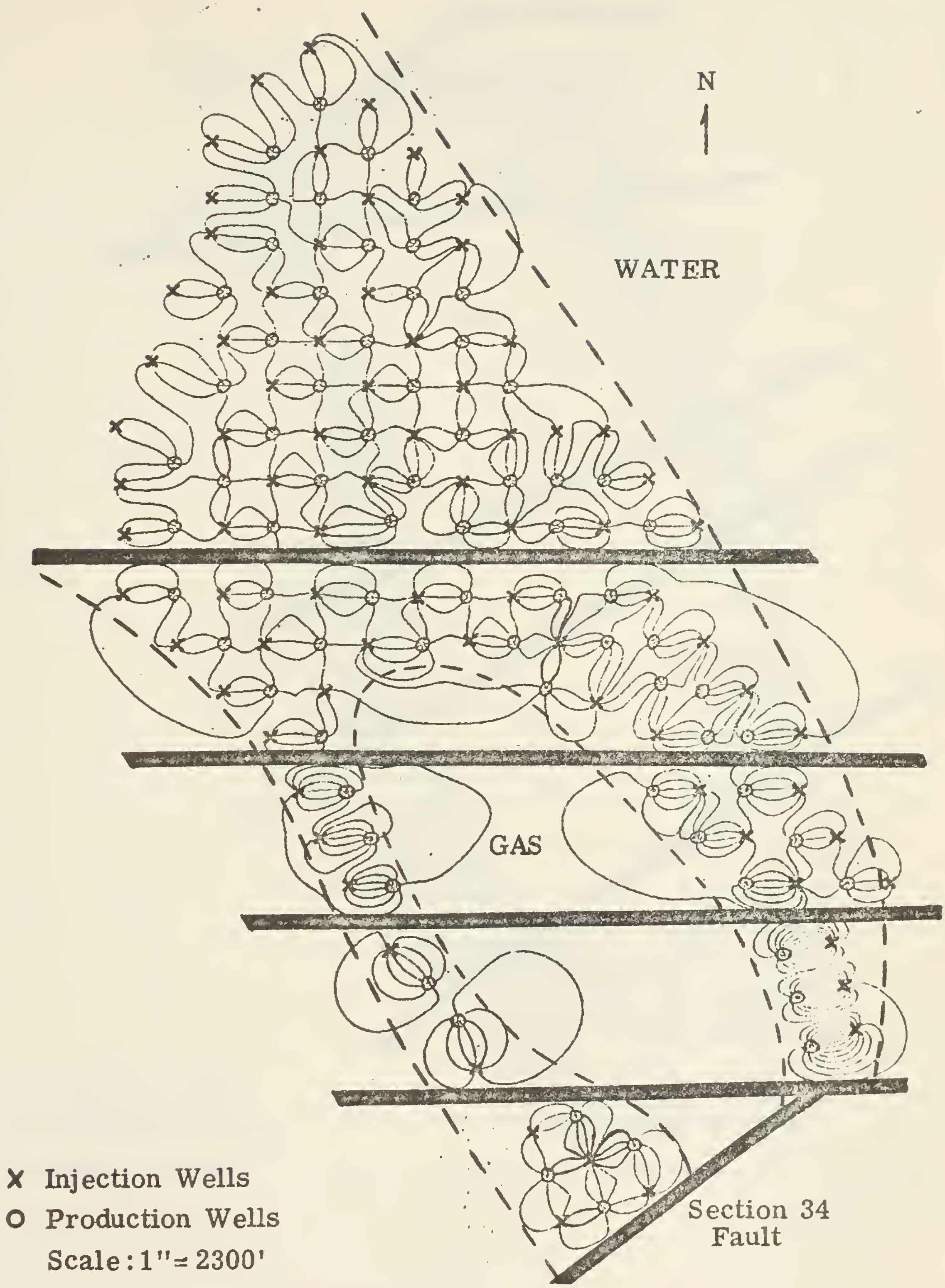


Figure 7 Model Generated Streamlines-Northern Half of Second Wall Creek Sand.

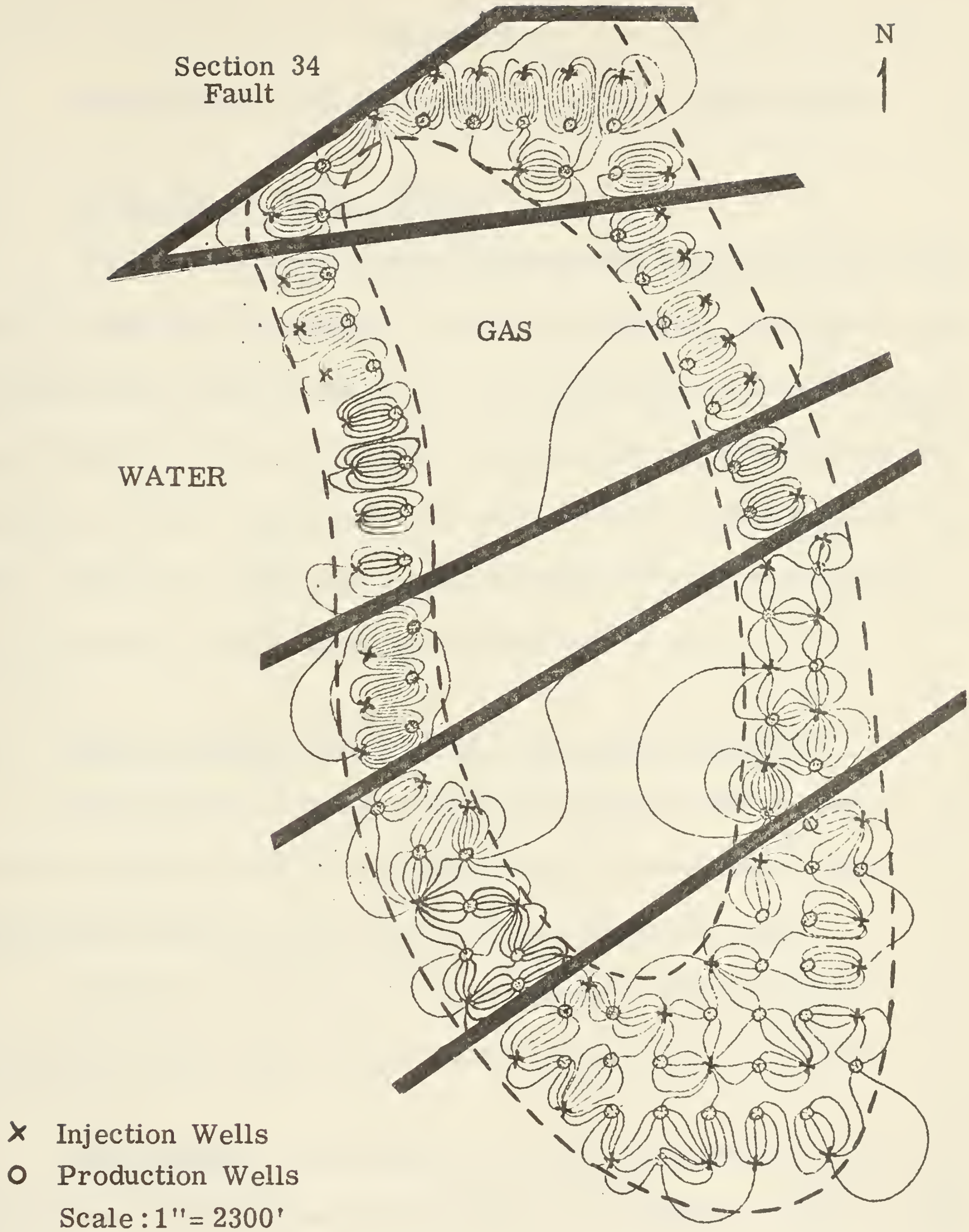


Figure 8 Model Generated Streamlines-Southern Half of Second Wall Creek Sand.

CHAPTER IV

RESULTS OF THE STREAMLINE MODEL SIMULATION

4.1 Predicted Production History

Figures 9, 10 and 11 show the predicted response of the Second Wall Creek Sand to a waterflood operated as previously described. It is predicted that 18,000,000 barrels of oil will be recovered in five years and 30,000,000 barrels of oil after ten years. Water breakthrough occurs around 1,000 days and the water-oil ratio climbs to over five after ten years. Ultimate recovery at a water-oil ratio of twenty is predicted to be around 32,000,000 barrels and takes twelve years.

4.2 Effects of Major Assumptions on Recovery Predictions

Although the oil recovery predicted agrees with the present reserve estimate of 28,800,000 barrels(9), the predictions of both quantity and time are only as good as the assumptions made.

In order to provide a proper perspective, the variables and assumptions which could most effect the results will be discussed.

Heterogeneity The model was run assuming that the reservoir sand in each fault block was homogeneous. Frequently, however, horizontally bedded sandstones exhibit different permeabilities among the individual stratum. The presence of high permeability strata will reduce the efficiency of the waterflood. The high permeability zones

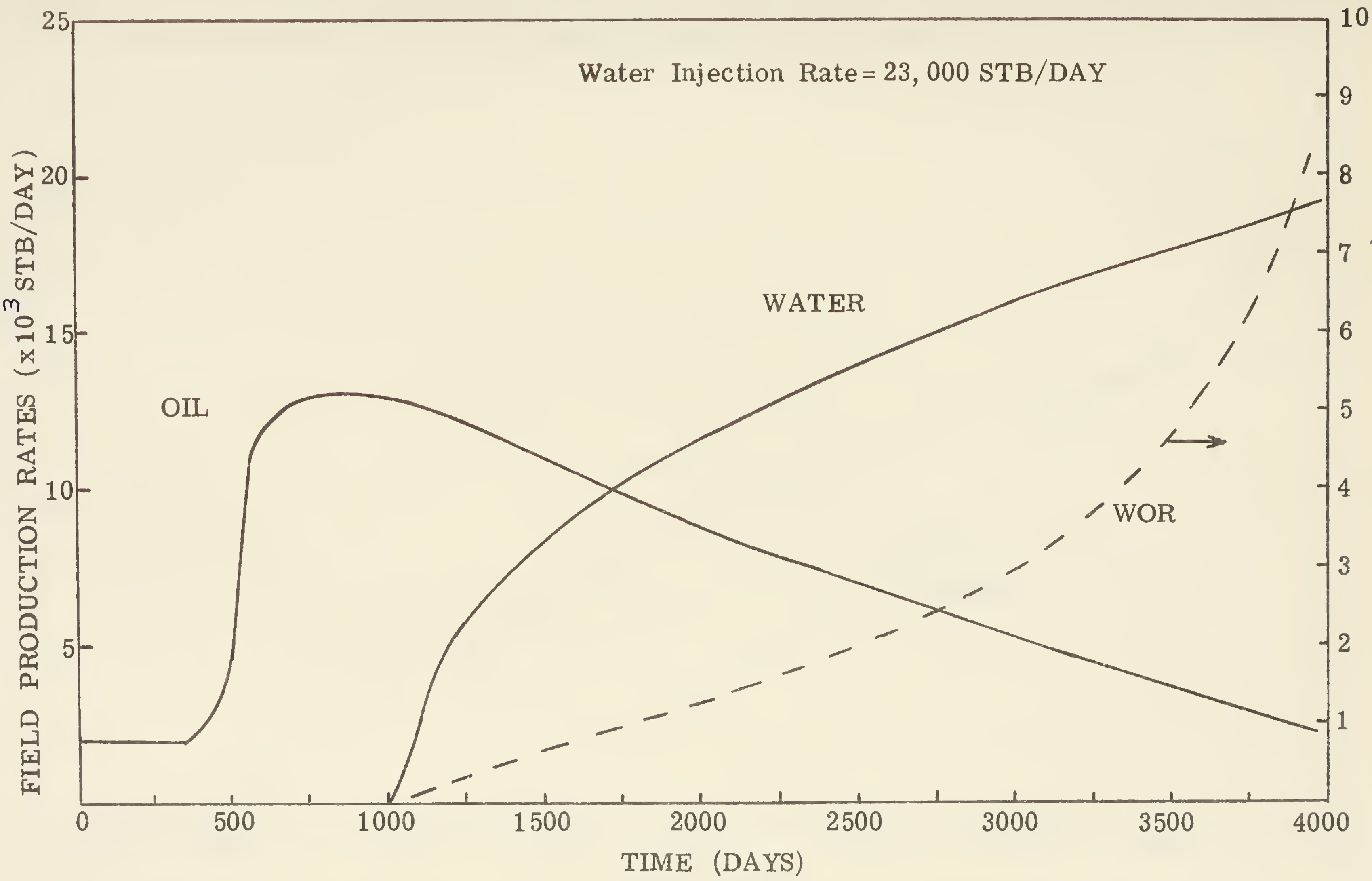


Figure 9 Oil and Water Production Rates During Waterflood Second Wall Creek Sand. Predictions Made Using Streamline Model.

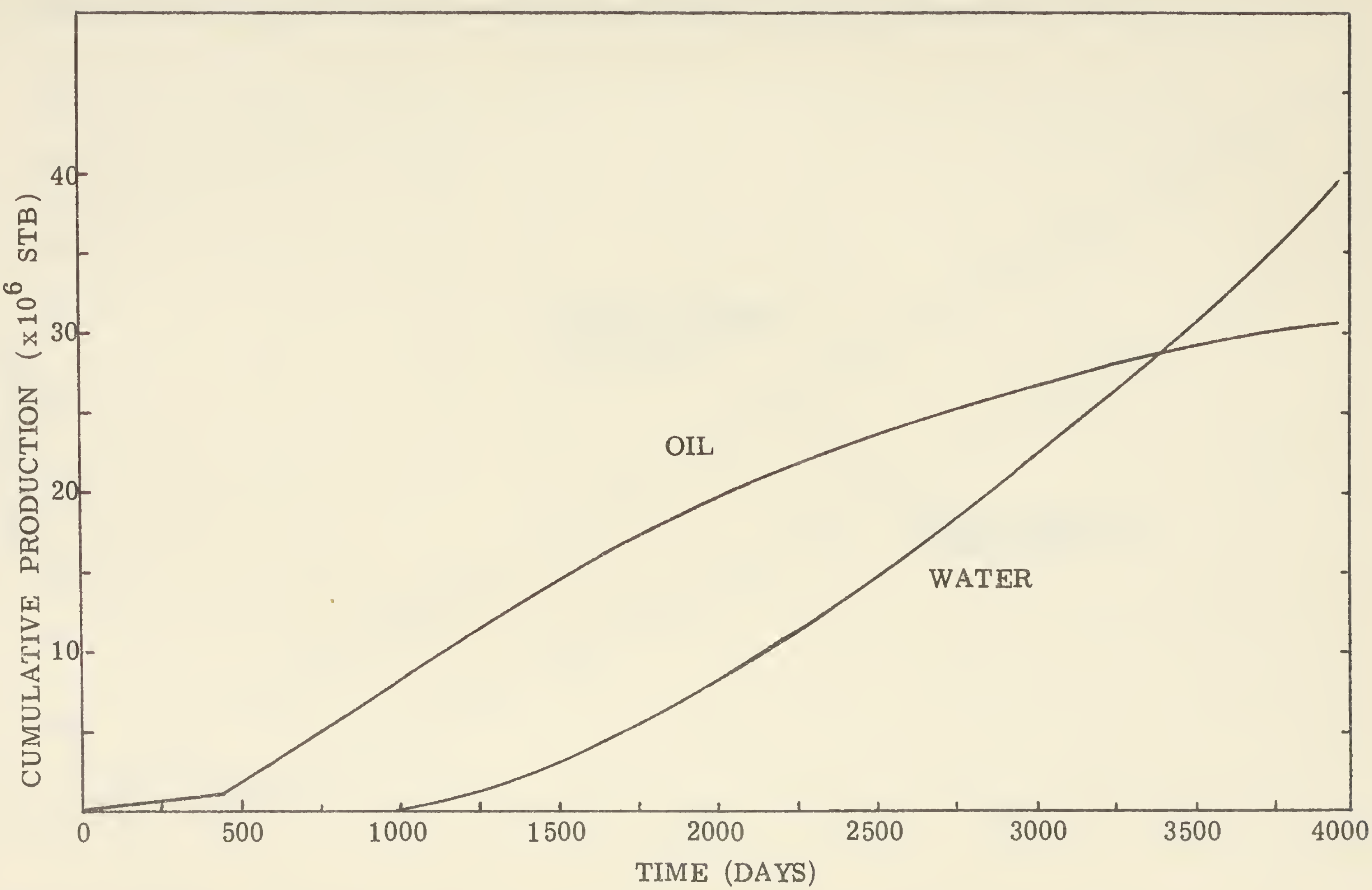


Figure 10 Oil and Water Production During Waterflood Second Wall Creek Sand. Predictions Made Using Streamline Model.

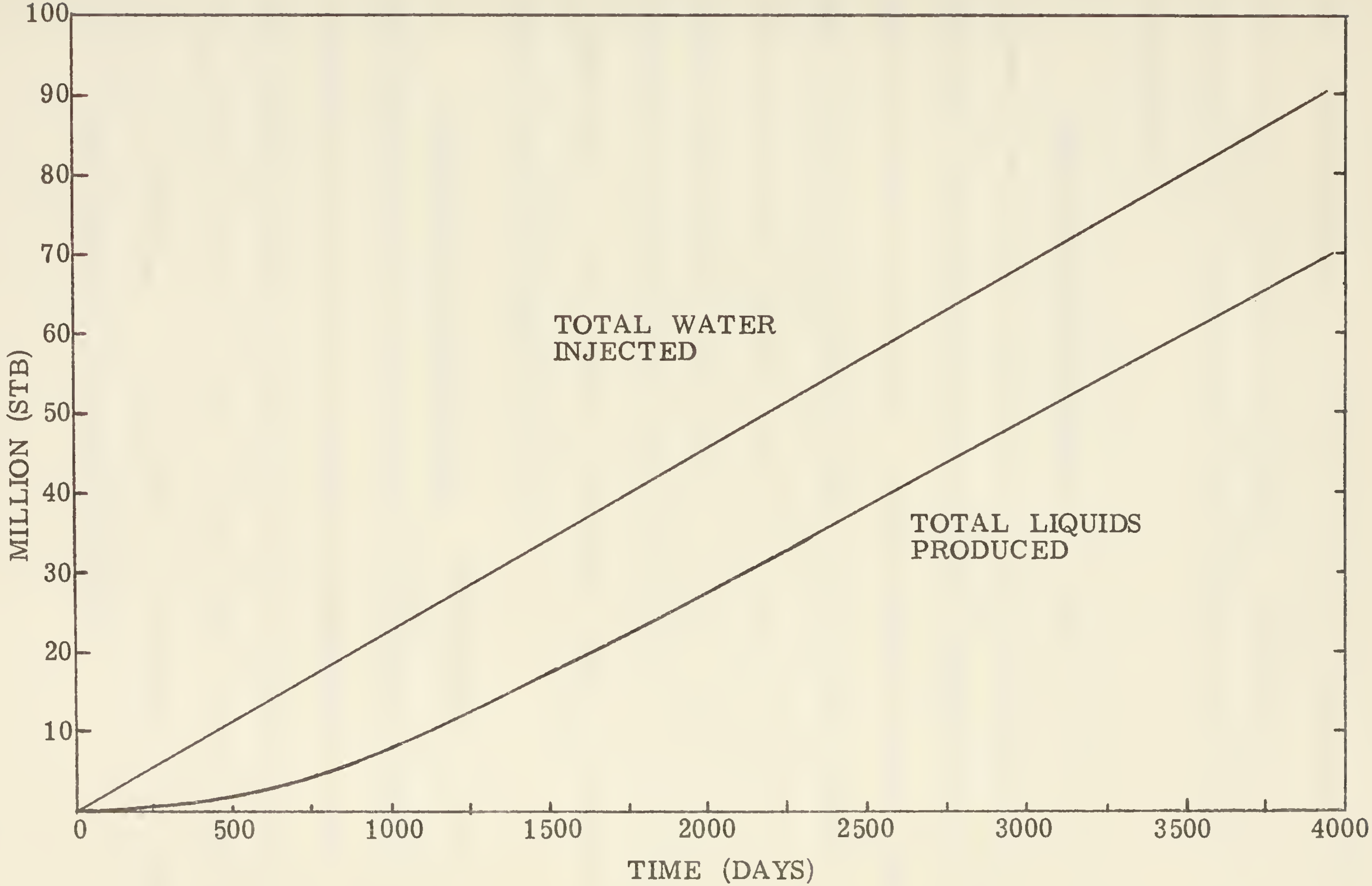


Figure 11 Water Injected and Total Liquids Produced During Waterflood Second Wall Creek Sand. Predictions Made Using Streamline Model.

water-out faster than the rest of the reservoir and then increase the water oil ratio much sooner than expected. If high permeability strata are shown to be a significant factor the predictions presented here will be optimistic.

Initial Gas and Oil Saturation The presence of free gas in the oil zone of the reservoir means that there will be a certain time lag, fill-up time, before the oil bank will reach the production wells. This time lag is approximately equal to the time required to inject enough water to fill the gas space and the space of the oil that is produced. The initial gas saturation chosen to represent the reservoir was 5%. If the quantity of gas present in the reservoir is actually less than 5% the oil production rate will increase earlier and if the space is assumed to be filled with oil, more oil will be recovered. If the gas saturation is greater than 5% the opposite will be true.

Production and Injection Rates The effect of increasing or decreasing the injection and production rates would be to condense or expand the time scale. If for example it was found that the reservoir could operate at injection and production rates 50% greater than those assumed here, the recovery that would have taken 1,500 days could be achieved in 1,000 days. See Appendix B for an example of rate adjustment to obtain uniform water breakthrough times.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The waterflood of the Second Wall Creek Sand will increase the total oil production to around 32,000,000 barrels. This is 15,000,000 barrels over that which could be expected from solution gas drive primary production. At the operating rates used the waterflood will require around twelve years.

5.2 Recommendations

1. It is recommended that the waterflooding of the Second Wall Creek Sand be planned and cost evaluations made. The streamline model developed here is well suited for studying development and operating considerations so that project economics can be evaluated.

2. Since the effects of high permeability strata on secondary recovery operations are always adverse and sometimes severe, it is recommended that the possible existence of such strata be thoroughly investigated during waterflood planning and development.

NOMENCLATURE

Symbol	Definition
A	Cross Sectional Area
h	Reservoir thickness
k	Permeability
l	Length; number of fluids
n	Number of wells
p	Pressure
q	Flow rate
Δs	Distance increment along path line
s	Saturation
Δt	Time step along path line
t	Time
u	Flux
v	Average fluid particle velocity
x, y, z	Rectangular coordinates
γ	Conductivity ratio
λ	Fluid mobility
μ	Viscosity
ρ	Density
o	Porosity
Φ	Potential

Subscripts

cw	Connate water
gi	Initial gas
gr	Residual gas
i	Index of wells; in
j	Index of particle location
k	Index of fluids
m	Mean
o	Oil; out
oi	Initial oil
or	Residual oil
s	Starting point of fluid particle
p	Production
w	Water
x	In the x-direction
y	In the y-direction
z	In the z-direction

APPENDICES

APPENDIX A

INDIVIDUAL WELL DATA

TABLE IV

WELL DATA—FAULT BLOCK 1

Refer to Figure 12

Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.	Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.
1	87.	29	21	96	32
2	54.	27	22	-96	32
3	-90.	30	23	48	24
4	52.	26	24	-72	24
5	-87.	29	25	-72	24
6	93	31	26	-78	26
7	56	28	27	84	28
8	-90	30	28	-90	30
9	-96	32	29	96	32
10	78	26	30	-96	32
11	-81	27	31	-96	32
12	90	30	32	48	24
13	-96	32	33	-72	24
14	96	32	34	72	24
15	48	24	35	-72	24
16	72	24	36	78	26
17	-78	26	37	-84	28
18	-81	27	38	90	30
19	87	29	39	-96	32
20	-93	31	40	96	32

TABLE IV (Continued)

Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.	Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.
41	48	24	61	-90	30
42	-72	24	62	81	27
43	72	24	63	48	24
44	-72	24	64	36	24
45	72	24	65	72	24
46	-78	26	66	-78	26
47	84	28	67	93	31
48	-90	30	68	-90	30
49	96	32	69	84.	28
50	-96	32	70	-84	28
51	96	32	71	48.	24
52	48	24	72	48.	24
53	-72	24	73	-78	26
54	-72	24	74	-78	26
55	-72	24	75	36	24
56	90	30	76	40	24
57	-90	30	77	48	24
58	90	30			
59	-90	30			
60	90	30			

Production well oil rates during fill-up equal 10 STB/Day

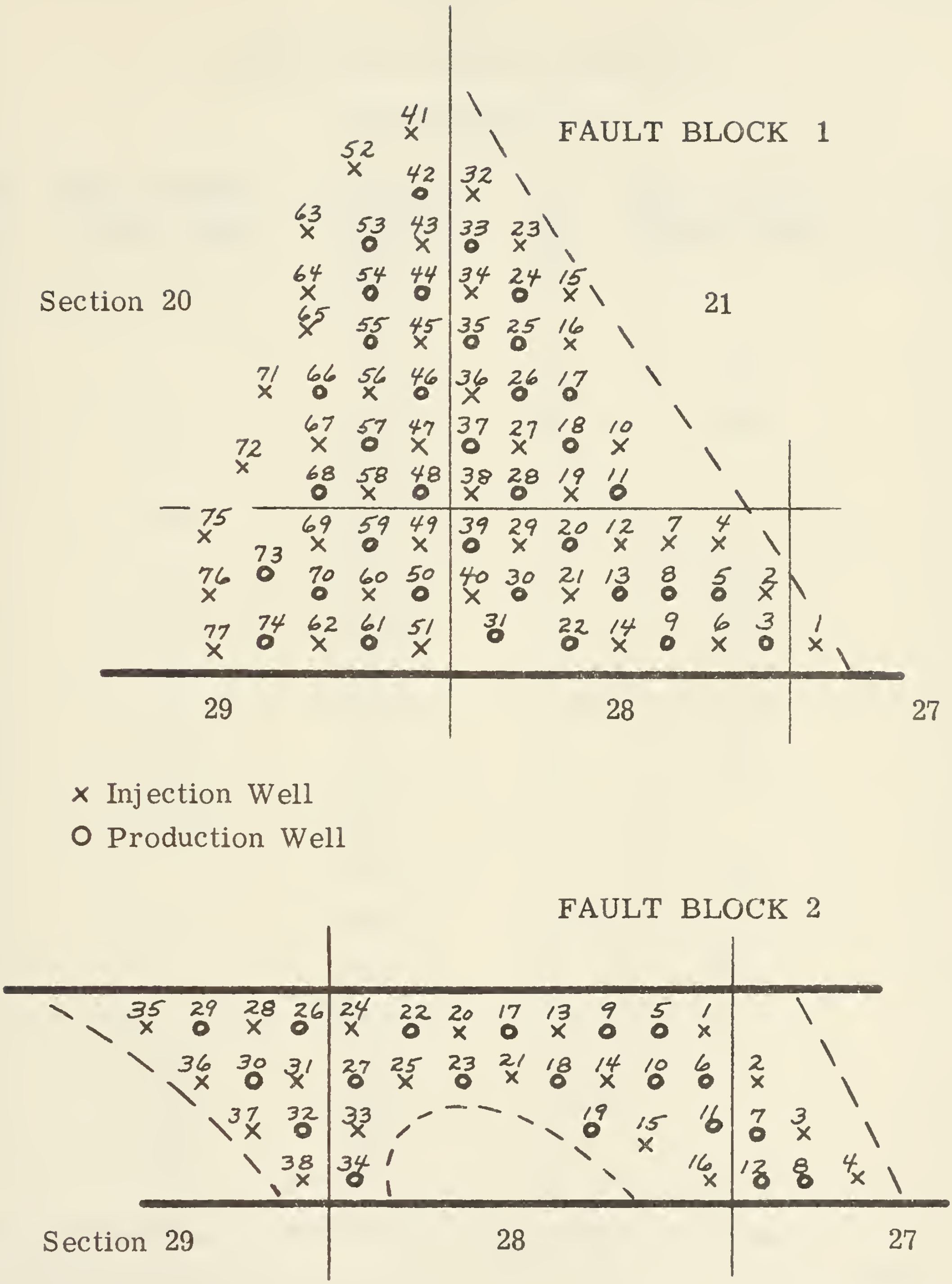


Figure 12 Well Locations for Fault Blocks 1 and 2.

TABLE V

WELL DATA—FAULT BLOCK 2

Refer to Figure 12

Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.	Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.
1	*	28	20	*	29.4
2	*	30.1	21	*	30.8
3	*	31.5	22	-175	29.4
4	*	32.2	23	-180	30.1
5	-175	28.7	24	*	28.7
6	-180	30.1	25	*	29.4
7	-195	32.2	26	-155	25.9
8	-205.	34.3	27	-175	28.7
9	-175	28.7	28	*	24.5
10	-185	30.8	29	-135	22.4
11	-200	32.9	30	-147	24.5
12	-210	35.	31	*	25.9
13	*	29.4	32	-160	26.6
14	*	30.8	33	*	28.7
15	*	33.6	34	-175	29.4
16	*	35.	35	*	21.0
17	-175	29.4	36	*	23.1
18	-185	30.8	37	*	25.9
19	-200	32.9	38	*	28.7

Production well oil rates during fill-up equal 20 STB/Day.

*Program calculates injection well rates based on reservoir thickness and steady state material balance.

TABLE VI

WELL DATA—FAULT BLOCK 3

Refer to Figure 13

Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.
1	140	35.
2	140	35
3	140	35
4	-178.5	35.7
5	-182	36.4
6	-178.5	35.7
7	218.4	36.4
8	226.2	37.7
9	226.2	37.7
10	-182	36.4
11	-192.5	38.5
12	-203.	40.6
13	-188.5	37.7
14	175	35.
15	182	36.4
16	203	40.6
17	-210	42.
18	-182	36.4

Production well oil rates during fill-up equal 20 STB/Day.

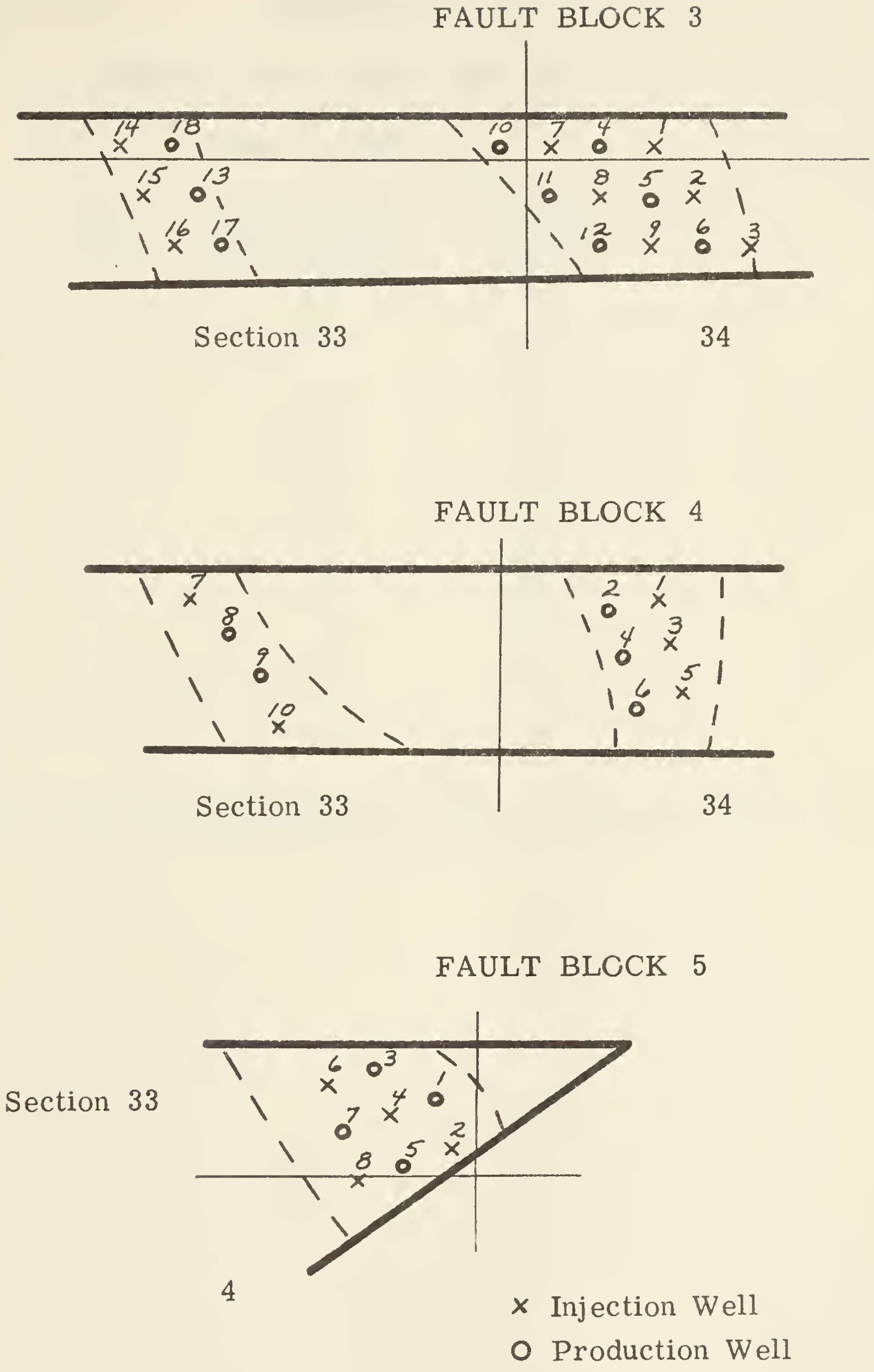


Figure 13 Well Locations for Fault Blocks 3-5.

TABLE VII

WELL DATA—FAULT BLOCK 4

Refer to Figure 13

Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.
1	88	44
2	-100	50
3	90	45
4	-100	50
5	86	43
6	-94	47
7	48	48
8	-48	48
9	-48	48
10	48	48

Production well oil rates during fill-up equal 10% of initial rate.

TABLE VIII

WELL DATA—FAULT BLOCK 5

Refer to Figure 13

Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.
1	-50	50
2	*	50
3	-50	50
4	*	48
5	-50	50
6	*	50
7	-46	46
8	*	46

Production well oil rates during fill-up equal 3 STB/Day.

* Program calculates injection well rates based on reservoir thickness and steady state material balance.

TABLE IX

WELL DATA—FAULT BLOCK 6

Refer to Figure 14

Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.
1	260	56
2	240	52
3	245	53
4	245	53
5	225	49
6	-340	58
7	-300	60
8	-300	60
9	-300	60
10	-285	57
11	-255	51
12	-275	55
13	300	60
14	-300	60
15	-270	54
16	250	48
17	305	52
18	-275	55

Production well oil rates during fill-up equal 25 STB/Day.

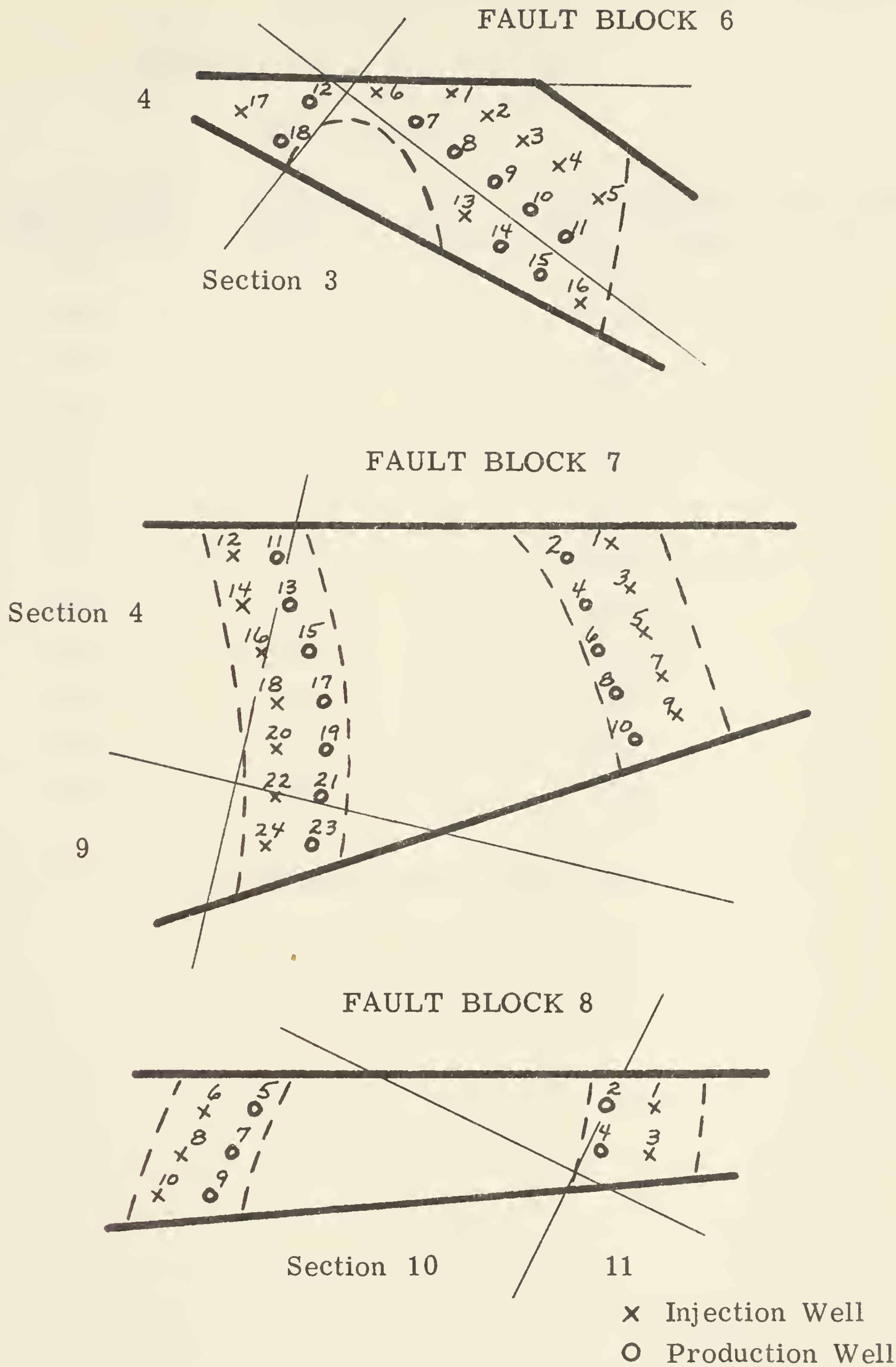


Figure 14 Well Locations for Fault Blocks 6-8.

TABLE X

WELL DATA—FAULT BLOCK 7

Refer to Figure 14

Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.	Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.
1	234	39	13	-282	47
2	-264	44	14	258	43
3	234	39	15	-288	48
4	-258	43	16	276	46
5	234	39	17	-288	48
6	-258	43	18	270	45
7	228	38	19	-282	47
8	-240	40	20	264	44
9	222	37	21	-276	46
10	-228	38	22	258	43
11	-270	45	23	-270	45
12	252	42	24	258	43

Production well rates during fill-up equal 25 STB/Day.

TABLE XI

WELL DATA—FAULT BLOCK 8

Refer to Figure 14

Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.
1	124	31
2	-124	31
3	124	30
4	-124	31
5	-168	42
6	168	42
7	-168	42
8	160	40
9	-168	42
10	156	39

Production well oil rates during fill-up equal 15 STB/Day.

TABLE XII

WELL DATA—FAULT BLOCK 9

Refer to Figure 15

Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.	Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.
1	*	27.7	14	-150	40
2	*	30.4	15	*	40
3	-120	29.	16	-150	40
4	-160	31.7	17	-200	40
5	*	30.4	18	*	40
6	*	35.6	19	-150	40
7	-135	33.	20	*	40
8	-200	40.	21	-150	40
9	*	35.6	22	-150	40
10	*	40	23	*	40
11	-155	37.6	24	*	40
12	-200	40.	25	-150	40
13	*	40			

Production well oil rates during fill-up equal 15 STB/Day.

* Program calculates injection well rates based on reservoir thickness and steady state material balance.

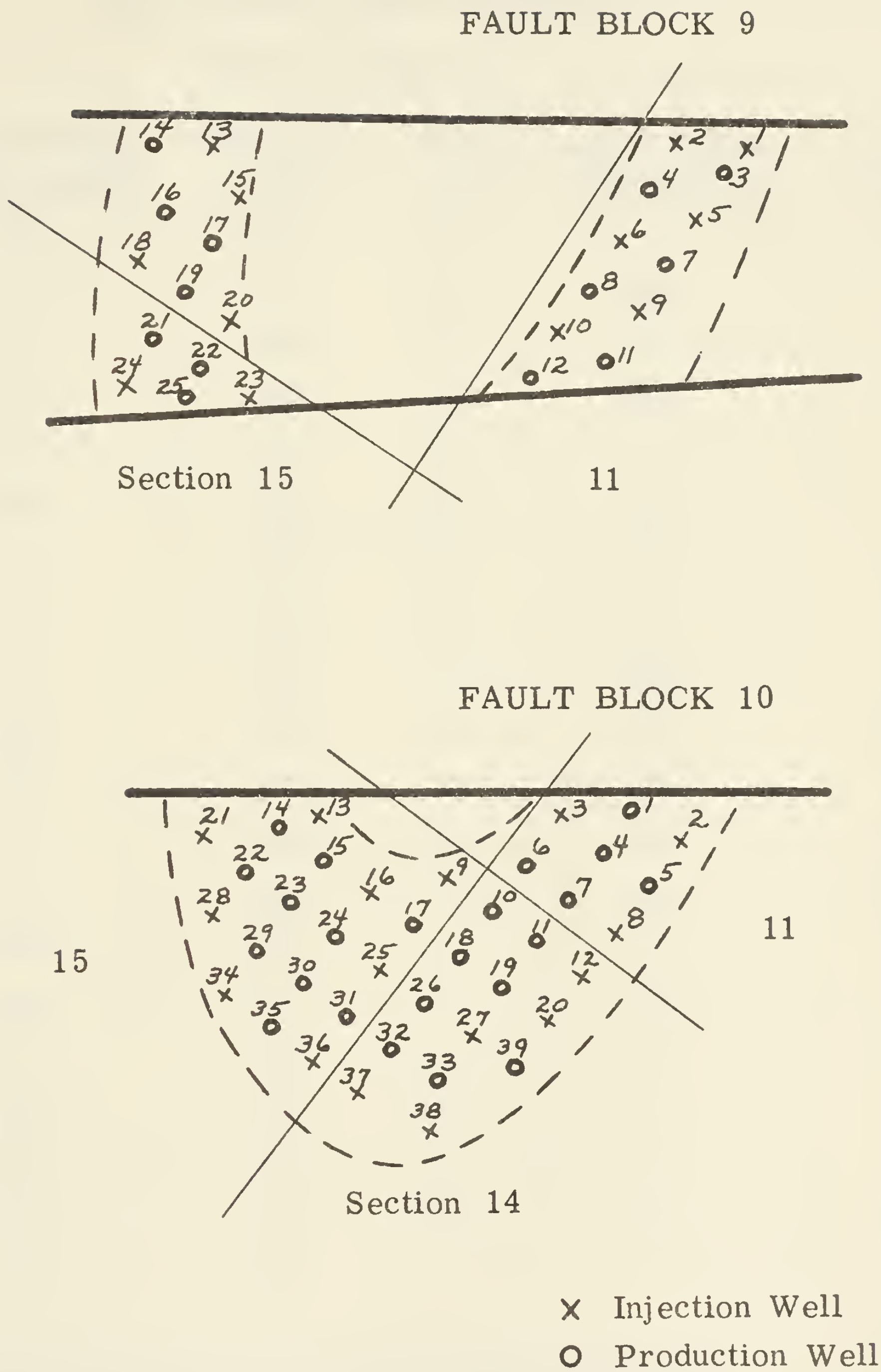


Figure 15 Well Locations for Fault Blocks 9 and 10.

TABLE XIII

WELL DATA—FAULT BLOCK 10

Refer to Figure 15

Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.	Well No.	Rate, STB/Day (+Inj, -Prod)	Thickness Ft.
1	-76	38	21	*	40
2	*	35	22	-80	40
3	*	40	23	-80	40
4	-76	38	24	-80	40
5	-70	35	25	*	40
6	-80	40	26	-76	38
7	-74	37	27	*	35
8	*	35	28	*	40
9	*	40	29	-80	40
10	-80	40	30	-78	39
11	-74	37	31	-76	38
12	*	34	32	-72	36
13	*	40	33	-70	35
14	-150	40	34	*	38
15	-150	40	35	-76	38
16	*	40	36	*	37
17	-80	40	37	*	36
18	-76	38	38	*	33
19	-72	36	39	-66	33
20	*	34			

Production well oil rates during fill-up equal 8 STB/Day.

* Program calculates injection well rates based on reservoir thickness and steady state material balance.

APPENDIX B

RATE ADJUSTMENT

ADJUSTMENTS OF INJECTION AND PRODUCTION RATES TO ACHIEVE UNIFORM WATER BREAKTHROUGH IN ALL FAULT BLOCKS

When the model response was inspected section by section it was found that some of the sections were watering-out faster than others. This situation is also possible in the field. If the injection and production rates cannot be sufficiently adjusted, certain sections would be watered-out and shut-in while others would be run longer until ultimate recovery.

If the rates can be adjusted enough the field can be operated so that all of the sections water-out at about the same time. The well rates used in the model were adjusted, with the total field injection rate held constant, to determine the effect of uniform water breakthrough from section to section.

The results, as shown in Figure 16, indicate that for the same period of operation the oil production was increased and the water production was decreased.

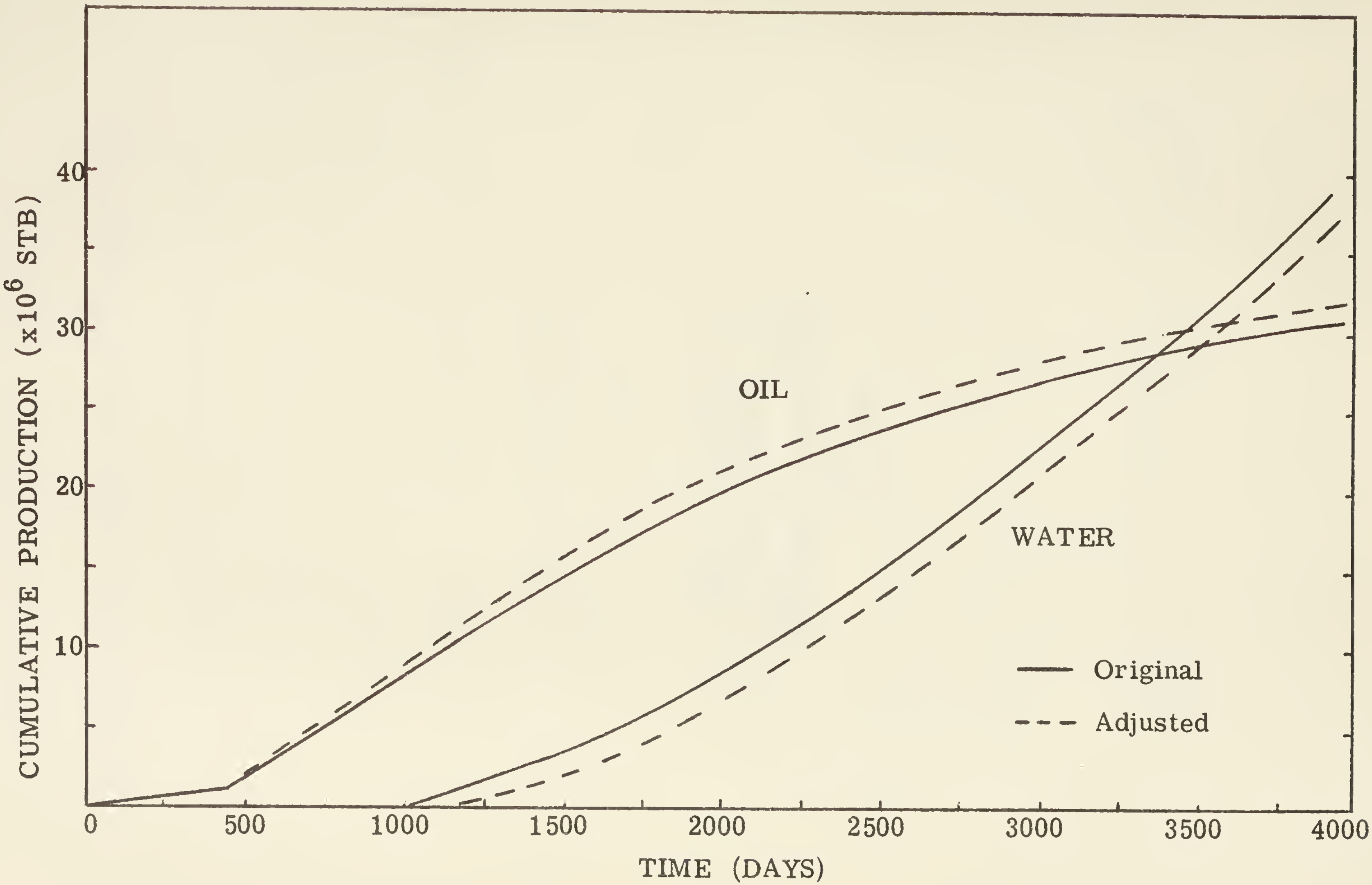


Figure 16 Oil and Water Production With Well Rates Adjusted for Uniform Water Breakthrough Times. Predictions Made Using Streamline Model.

APPENDIX C

COMPUTER PROGRAM

1. Program Listing
2. Sample Data Deck

```
      PROGRAM OLBNKVT(INPUT,OUTPUT)
C
C
C         A STREAMLINE MODEL FOR WATERFLOOD SIMULATION
C
C
C        THIS MODEL IS SPECIFICALLY DESIGNED TO SIMULATE A
C      WATERFLOOD OPERATION IN WHICH AN OIL BANK IS FORMED AND
C      MOVES THROUGH THE RESERVOIR.  THE MODEL IS CAPABLE OF
C      HANDLING RESERVOIRS WITH THICKNESS VARIATIONS AND
C      IRREGULAR BOUNDARIES.
C
C      REFERENCES:
C
C        LEBLANC,J.L., AND CAUDLE,B.H., A STREAMLINE MODEL FOR
C          SECONDARY RECOVERY,  SOC. PET. ENGR. J. (1971),II,7.
C        RUST,C.B., A STREAMLINE MODEL FOR OIL BANK BUILDUP IN
C          A WATERFLOOD, M.S. THESIS, THE UNIVERSITY OF TEXAS AT
C          AUSTIN (MAY, 1972).
C        WESSELS,J.W., APPLICATION OF THE STREAMLINE RESERVOIR
C          MODEL TO RESERVOIRS HAVING VARIATIONS IN FORMATION
C          THICKNESS, M.S. THESIS, THE UNIVERSITY OF TEXAS AT AUSTIN
C          (MAY, 1973).
C
C      DOCUMENTED BY: K.E.GOLTZ (MARCH,1975)
C
C
C                          ********************************
C                          *  SCHEMATIC PROGRAM FLOW CHART  *
C                          ********************************
C
C
C
C                                -------------------
C                                I READ INPUT DATA  I
C                                -------------------
C                                        I
C                     ----------------------------------------
C                     I  COMPUTE STREAMLINE STARTING POINTS,  I
C                     I   SOURCE AND SINK PRESSURES           I
C                     ----------------------------------------
C                                        I
C                          ------------------------------
C   -----------------------I  ITERATE EACH TIME PERIOD   I
C   I                      ------------------------------
C   I                                    I
C   I                       ---------------------------------
C   I  ---------------------I  ITERATE EACH PRODUCTION WELL   I
C   I  I                    ---------------------------------
C   I  I                                 I
C   I  I                       ------------------------------
C   I  I  ---------------------I  ITERATE EACH STREAMLINE    I
C   I  I  I                    ------------------------------
C   I  I  I                              I
C   I  I  I               ---------------------------------------------
C   I  I  I  -------------I  COMPUTE VELOCITIES AND TIME INCREMENTS    I
C   I  I  I  I            I    AT EACH POINT ALONG STREAMLINE          I
C   I  I  I  I            ---------------------------------------------
C   I  I  I  I                           I
C   I  I  I  I          -----------------------------------------------
C   I  I  I  I          I  MOVE FLUID PARTICLE ALONG STREAMLINE USING  I
C   I  I  I  I          I  FINITE DIFFERENCE APPROX. OF DARCYS LAW     I
```

```
C   I  I  I  I   ---------------------------------------------------
C   I  I  I  I                         I
C   I  I  I  I         ----------------------------------------
C   I  I  I  I         I  ACCUMULATE STREAMLINE PRODUCTION    I
C   I  I  I  I         ----------------------------------------
C   I  I  I  I                         I
C   I  I  I  I         ----------------------------------------
C   I  I  I  I         I  TEST FOR BREAKTHROUGH OF FLUID      I
C   I  I  I  I         I  PARTICLES INTO PRODUCTION WELLS,    I
C   I  I  I  I         I  ADJUST STREAMLINE PRODUCTION        I
C   I  I  I  I         I   RATES AS REQUIRED                  I
C   I  I  I  I         ----------------------------------------
C   I  I  I  I                         I
C   I  I  I  I    NO     ---------------------------------
C   I  I  I  ---------I  TEST FOR END OF TIME PERIOD    I
C   I  I  I              ---------------------------------
C   I  I  I                            I  YES
C   I  I  I       NO      --------------------------------
C   I  I  -------------I  TEST FOR ALL STREAMLINES     I
C   I  I                  --------------------------------
C   I  I                               I  YES
C   I  I          NO    --------------------------------------
C   I  --------------I   TEST FOR ALL PRODUCTION WELLS     I
C   I                   --------------------------------------
C   I                                  I  YES
C   I                     ----------------------------------------
C   I                     I  PRINT/PLOT WELL AND FIELD RESULTS  I
C   I                     ----------------------------------------
C   I                                  I
C   I                    NO   ---------------------
C   ----------------------I  TEST FOR TOTAL TIME  I
C                             ---------------------
C                                      I  YES
C                               ---------
C                               I  STOP  I
C                               ---------
C
C
C *****************************************************************
C
C              INPUT DATA DEFINITIONS
C
C    POR = POROSITY (DECIMAL)
C    SCW = SATURATION CONNATE WATER (DECIMAL)
C    SOI = SATURATION OIL INITIAL (DECIMAL)
C    SOR = SATURATION OIL RESIDUAL (DECIMAL)
C    SGR = SATURATION GAS RESIDUAL (DECIMAL)
C    SGOR = SOLUTION GAS-OIL RATIO (SCF/BBL AT RES. CONDITIONS)
C    NP = NUMBER OF PRODUCTION WELLS
C    NI = NUMBER OF INJECTION WELLS
C    NBW = NUMBER OF IMAGE WELLS USED TO BOUND PATTERN
C    NBP = NUMBER OF POINTS USED TO DEFINE BOUNDARY
C    NST = NUMBER OF STREAMLINES FOR LOWEST RATE PRODUCTION WELL
C    NXH = NUMBER OF X-DIRECTION ENTRIES IN THICKNESS GRID
C    NYH = NUMBER OF Y-DIRECTION ENTRIES IN THICKNESS GRID
C    NEDIT = 0 OR 1
C      IF 0 OR BLANK-PROGRAM WILL BALANCE PROD/INJ RATES
C      IF 1  PROGRAM INTERNAL BALANCE FEATURE IS DEFEATED
C    H = AVERAGE RESRVOIR THICKNESS,FT (USED FOR IMAGE WELLS)
C    RI = RADIUS OF STARTING AND ENDING CIRCLES,FT
C    DELT = TIME INCREMENT (DAYS) FOR UPDATING CONSTANT PRESSURE
C          CORRECTION FACTOR. SINCE DELT MUST START OUT SMALL BUT
```

```
C           BECOMES LESS CRITICAL AS THE SOLUTION PROGRESSES,
C           THE VALUE OF DELT IS MULTIPIED BY TEN AFTER THE
C           OIL BANK BREAKS THROUGH IN THE FIRST STREAMLINE.
C     DELP = TIME INCREMENT FOR PRINT AND PLOT (DAYS)
C             FIRST PRINT/PLOT IS MADE AT DELT,THEN EVERY DELP
C     TMX = MAXIMUM TIME FOR SOLUTION (DAYS)
C     QMNP = LOWEST PRODUCTION WELL RATE (STB/DAY)
C     QMNI = LOWEST INJECTION WELL RATE (STB/DAY/FT)
C     XMX = ABSOLUTE X DIMENSION AT WHICH STREAMLINES ARE CUT OFF
C     YMX = ABSOLUTE Y DIMENSION AT WHICH STREAMLINES ARE CUT OFF
C     GMB,OMB,WMB = GAS,OIL AND WATER MOBILITIES
C     XW(I),YW(I) = X,Y COORDINATES OF WELL LOCATION
C     HI(I) = THICKNESS OF RESERVOIR AT WELL,FT
C     Q(I) = WELL INITIAL OIL PRODUCTION RATE (STB/DAY)
C     QO(I) = WELL PRESENT (FILL-UP) OIL PRODUCTION RATE (STB/DAY)
C     GOR(I) = WELL GAS-OIL RATIO (SCF/BBL AT RES. CONDITIONS)
C     XB(I),YB(I) = X,Y COORDINATES OF BOUNDARY POINTS
C     XH(I),YH(I) = X,Y COORDINATE VALUES FOR THICKNESS GRID
C     HT(I,J) = VALUES OF THICKNESS CORRESPONDING TO COORDINATES
C              OF THICKNESS GRID
C
C **********************************************************************
C
      COMMON/AAA/ XW(125),YW(125),HI(125),Q(125),XB(125),
     1YB(125),NBP,NP,NI,NBW,H
      COMMON/BBB/ C(55,55),D(55),QI(55)
      COMMON/CCC/ X(80,20),Y(80,20),XO(80,20),YO(80,20),
     1WQ(80,20),SCL,XMX,YMX,NST,QMNP,RGO(80,20),
     2SGOR,NPIW,TMEI
      DIMENSION TSUM(80,20),PP(80,20),PI(80,20),CO(80,20),
     1CW(80,20),QO(125),GOR(125),OQ(80,20),
     2XH(20),YH(20),HT(20,20)
      READ 530, POR,SCW,SOI,SOR,SGR,SGOR
      READ 540, NP,NI,NBW,NBP,NST
      READ 540, NXH,NYH,NEDIT
      READ 530, H,RI,DELT,DELP,TMX,QMNP
      READ 530, QMNI,XMX,YMX,GMB,OMB,WMB
      DELTT=DELT*10.
      NCOUNT=0
      PLTFT=0.9*XMX/YMX+0.45
      TOTFT=0.7+PLTFT
      NPIW=NP+NI
      NPIBW=NPIW+NBW
      READ 550, (XW(I),YW(I),HI(I),Q(I),QO(I),GOR(I),I=1,NPIBW)
      READ 560, (XB(I),YB(I),I=1,NBP)
C
C        CONVERT SURFACE RATES TO RESERVOIR RATES
C          FVF = 1.2
C
      DO 9 I=1,NPIW
      Q(I)=Q(I)*1.2
    9 QO(I)=QO(I)*1.2
      QMNP=QMNP*1.2
      QMNI=QMNI*1.2
      PRINT 590
      PRINT 480, NP,NI,NBW,NBP,NST
      PRINT 490, H,DELT,TMX,RI
      PRINT 500, DELP,XMX,YMX,QMNP
      PRINT 510, POR,SCW,SOI,SOR,SGR
      PRINT 520, OMB,WMB,GMB
      PRINT 550, (XW(I),YW(I),HI(I),Q(I),QO(I),GOR(I),I=1,NPIBW)
      PRINT 530, (XB(I),YB(I),I=1,NBP)
```

```
C
C         BALANCE INJECTION WELL RATES CONSIDERING RESERVOIR
C         THICKNESS AND STEADY STATE OPERATION
C
      IF(NEDIT .GT. 0) GO TO 31
      SMQI=0.0
      SMQP=0.0
      DO 20 I=1,NPIW
         IF (Q(I).LT.0.0) GO TO 10
      SMQI=SMQI+Q(I)
         GO TO 20
 10   CONTINUE
      SMQP=SMQP+Q(I)/HI(I)
 20   CONTINUE
      DO 30 I=1,NPIW
         IF (Q(I).LT.0.0) GO TO 30
      Q(I)=-Q(I)*SMQP*HI(I)/SMQI
 30   CONTINUE
      GO TO 32
 31   PRINT 595
 32   CONTINUE
C
C         CHECK IF OIL BANK WILL FORM
C
         IF (SOR.LT.SOI) GO TO 40
      PRINT 570
         GO TO 470
 40   CONTINUE
C
C         CONVERT FIELD UNITS TO CGS
C
      DO 50 I=1,NPIBW
      XW(I)=XW(I)*30.48
      YW(I)=YW(I)*30.48
      QO(I)=QO(I)*1.8401
      HI(I)=HI(I)*30.48
      Q(I)=Q(I)*1.8401
         IF (I.LE.NPIW) GO TO 50
      HI(I)=H*30.48
 50   CONTINUE
      DO 60 I=1,NBP
      XB(I)=XB(I)*30.48
      YB(I)=YB(I)*30.48
 60   CONTINUE
      H=H*30.48
      DO 70 I=1,NXH
      READ 580, (HT(I,J),J=1,NYH)
 70   CONTINUE
      READ 580, (XH(I),I=1,NXH)
      READ 580, (YH(I),I=1,NYH)
      DO 80 I=1,NXH
      DO 80 J=1,NYH
      HT(I,J)=HT(I,J)*30.48
 80   CONTINUE
      DO 90 I=1,NXH
      XH(I)=XH(I)*30.48
 90   CONTINUE
      DO 100 I=1,NYH
      YH(I)=YH(I)*30.48
 100  CONTINUE
      RI=RI*30.48
      DELT=DELT*86400.
```

```
      DELTT=DELTT*86400.
      DELP=DELP*86400.
      TMX=TMX*86400.
      QMNP=QMNP*1.8401
      XMX=XMX*30.48
      YMX=YMX*30.48
      QMNI=QMNI*1.8401
C
C        SUBROUTINE BOUND CALCULATES THE NECESARY RATES
C      FOR PREVIOUSLY SELECTED IMAGE WELLS SO THAT THE
C      STREAMLINES ARE CONFINED WITHIN THE RESERVOIR
C      BOUNDARIES.
C
      CALL BOUND
      PRINT 600
C
C        CHECK QMNI AND CALCULATE VELOCITIES NEAR
C      INJECTION AND PRODUCTION WELLS
C
      DO 110 I=1,NPIBW
         IF (Q(I).LT.0.0) GO TO 110
      IF (Q(I)/HI(I).LT.QMNI) QMNI=Q(I)/HI(I)
 110  CONTINUE
      VLCI=0.5*QMNI/RI
      VLCP=0.4*QMNP/H/RI
      NTSL=0
C
C
C        THIS SECTION STARTS A STREAMLINE ON THE CIRCLE OF A
C      PRODUCTION WELL AND FOLLOWS IT BACKWARDS TO LOCATE THE
C      PROPER INJECTION WELL.  THIS PROCESS IS CARRIED OUT FOR
C      ALL PRODUCTION WELLS AND ALL STREAMLINES.  THE
C      STREAMLINE STOPS AT A POINT WITHIN THE CIRCLE OF AN
C      INJECTION WELL.  THIS POINT BECOMES THE STARTING POINT
C      WHEN THE STREAMLINE IS FOLLOWED IN THE FORWARD DIRECTION
C      TO ACCUMULATE THE PRODUCTION HISTORY.
C        AS THE STREAMLINES ARE BEING FOLLOWED A PLOT OF THEIR
C      TRACE IS MADE. (NOTE THAT ALL PLOT STATEMENTS HAVE
C      ASTERISKS IN THEIR STATEMENT NUMBERS.)
C
C  **********************************************************************
C
C                  PROGRAM VARIABLES
C
C
C     J = INDEX FOR WELLS
C     K = INDEX FOR STREAMLINES
C
C     XI,YI = POSITION ON STREAMLINE OF FLUID PARTICLE BEING TRACED
C     VX,VY = VELOCITY OF FLUID PARTICLE IN X AND Y DIRECTIONS
C     PP = PRESSURE AT PRODUCTION WELL (SINK)
C     PI = PRESSURE AT INJECTION WELL (SOURCE)
C     X(J,K),Y(J,K) = STARTING POINTS FOR WATER FRONT FROM INJ. WELL
C     XO(J,K),YO(J,K) = STARTING POINTS FOR OIL FRONT FROM INJ. WELL
C     TSUM(J,K) = SUMMATION OF TIME
C     RGO(J,K) = STREAMLINE GAS-OIL RATIO
C     OQ(J,K) = STREAMLINE OIL RATE
C     CO(J,K) = STREAMLINE CUMMULATIVE OIL PRODUCTION
C     WQ(J,K) = STREAMLINE WATER RATE
C     CW(J,K) = STREAMLINE CUMMULATIVE WATER PRODUCTION
C     SCL = PLOT SCALE FACTOR
C     NSL = NUMBER OF STREAMLINES FOR THE PRODUCTION WELL
```

```
C           BEING WORKED ON
C      DT = TIME INCREMENT FOR SMALL STEP TAKEN.  STEP SIZE IS
C           EQUAL TO .25*RI.  RI NEED NOT BE SMALLER THAN
C           1/50TH OF THE DISTANCE BETWEEN WELLS.
C
C  ***********************************************************************
C
C
      SCL=5.238/YMX
      XM=2.25*XMX*SCL
      CALL BGNPLT (4LPLOT,XM,25,25)
      CALL PLT (1.125*XMX*SCL,1.125*YMX*SCL,-3)
      CALL PLT (XB(NBP)*SCL,YB(NBP)*SCL,3)
      DO 120 I=1,NBP
      CALL PLT (XB(I)*SCL,YB(I)*SCL,2)
  120 CONTINUE
      DO 140 I=1,NPIW
         IF (Q(I).GE.0.0) GO TO 130
      CALL SYMBOL (XW(I)*SCL,YW(I)*SCL,.07,1,0,-1)
         GO TO 140
  130 CONTINUE
      CALL SYMBOL (XW(I)*SCL,YW(I)*SCL,.07,7,0,-1)
  140 CONTINUE
      DO 220 J=1,NPIW
         IF (Q(J).GE.0.0) GO TO 220
      NSL=-NST*Q(J)/QMNP+0.5
C
C          THE STREAMLINE STARTING POSITIONS ARE EVENLY SPACED
C        AROUND THE PRODCTION WELL
C
      DO 210 K=1,NSL
      XI=XW(J)+RI*COS(1.0+K*6.2832/NSL)
      YI=YW(J)+RI*SIN(1.0+K*6.2832/NSL)
      CALL PLT (XI*SCL,YI*SCL,3)
      PP(J,K)=0.0
      DO 150 L=1,NPIBW
      PP(J,K)=PP(J,K)-Q(L)/HI(L)*ALOG((XI-XW(L))**2+(YI-YW(L))**2)
  150 CONTINUE
  160 CONTINUE
         IF (ABS(XI).GT.XMX) GO TO 180
         IF (ABS(YI).GT.YMX) GO TO 180
      VX=0.0
      VY=0.0
      DO 170 L=1,NPIBW
      DEN=(XI-XW(L))**2+(YI-YW(L))**2
      VX=VX-Q(L)*(XI-XW(L))/(DEN*HI(L))
      VY=VY-Q(L)*(YI-YW(L))/(DEN*HI(L))
  170 CONTINUE
      VT=SQRT(VX**2+VY**2)
      DT=0.25*RI/VT
      XI=XI+DT*VX
      YI=YI+DT*VY
      CALL PLT (XI*SCL,YI*SCL,2)
C
C          CHECK IF THE STREAMLINE HAS REACHED AN INJECTION WELL.
C        THE VELOCITY OF THE FLUID PARTICLE IS CHECKED FIRST TO
C        SEE IF IT IS LARGE ENOUGH TO BE IN THE VICINITY OF AN
C        INJECTION WELL.  IF IT IS, EACH INJECTION WELL IS THEN CHECKED.
C
         IF (VT.LE.VLCI) GO TO 160
      DO 200 LL=1,NPIBW
         IF (Q(LL).LE.0.0) GO TO 200
```

```
      RAD=SQRT((XI-XW(LL))**2+(YI-YW(LL))**2)
         IF (RAD.GT.RI) GO TO 200
 180  CONTINUE
      NTSL=NTSL+1
      X(J,K)=XI
      Y(J,K)=YI
      TSUM(J,K)=0.0
      XO(J,K)=XI
      YO(J,K)=YI
      PI(J,K)=0.0
      DO 190 LK=1,NPIBW
      PI(J,K)=PI(J,K)-Q(LK)/HI(LK)*ALOG((XI-XW(LK))**2+(YI-YW(LK))**2)
 190  CONTINUE
      RGO(J,K)=GOR(J)
      IF (SCW+SOI+SGR.GE.1.0) RGO(J,K)=SGOR
      OQ(J,K)=QO(J)/NSL
      CO(J,K)=0.0
      WQ(J,K)=0.0
         GO TO 210
 200  CONTINUE
         GO TO 160
 210  CONTINUE
      CW(J,K)=0.0
 220  CONTINUE
      CALL PLT (0.0,0.0,999)
      PRINT 610
C
C        END OF RUNBACK SECTION
C
      CTR=1.0
      PRINT 590
      TSTOP=DELT
      TSMP=DELT
      NBP1=NBP+1
 230  CONTINUE
      SMCTY=0.0
C
C
C        THIS SECTION STARTS THE STREAMLINE AT THE INJECTION
C       WELL FOUND ABOVE AND FOLLOWS IT IN THE FORWARD DIRECTION
C       TOWARD THE PRODUCTION WELL.  THE MOVEMENTS OF THE OIL AND
C       WATER FRONTS ARE CLOSELY WATCHED TO DETERMINE WHEN THEY
C       BREAKTHROUGH INTO THE PRODUCTION WELL.  THE PRODUCTION
C       HISTORIES ARE ACCUMULATED AS THE FRONTS MOVE.
C        LOOPS 420 AND 410 ARE DONE FOR ALL WELLS AND ALL
C       STREAMLINES UNTIL TIME EQUALS TSTOP.  THEN THE CONSTANT
C       PRESSURE CORRECTION FACTOR (CTR) IS UPDATED AND THE
C       RESULTS ARE PRINTED IF DESIRED.
C
C   ***************************************************************
C
C              ADDITIONAL PROGRAM VARIABLES
C
C     CTY = CONDUCTIVITY RATIO
C     CTR = CONDUCTIVITY RATIO CORRECTION FACTOR
C     TSTOP = TIME TO STOP AND UPDATE CTR
C     TSMP = TIME TO PRINT AND PLOT
C     XI,YI = LOCATION OF WATER FRONT ON STREAMLINE BEING FOLLOWED
C     XOI,YOI = LOCATION OF OIL FRONT ON STREAMLINE BEING FOLLOWED
C
C   ***************************************************************
C
```

```
      DO 420 J=1,NPIW
         IF (Q(J).GE.0.0) GO TO 420
      NSL=-NST*Q(J)/QMNP+0.5
      DO 410 K=1,NSL
      CTY=0.0
         IF (ABS(X(J,K)).GT.XMX) GO TO 410
         IF (ABS(Y(J,K)).GT.YMX) GO TO 410
         IF (WQ(J,K).GT.0.0) GO TO 400
      XI=X(J,K)
      YI=Y(J,K)
      TSUMI=TSUM(J,K)
      XOI=XO(J,K)
      YOI=YO(J,K)
  240 CONTINUE
C
C       DETERMINE THICKNESS OF RESERVOIR AT LOCATION OF FRONTS
C
      DO 250 M=1,NXH
         IF (XI.LT.XH(M)) GO TO 260
  250 CONTINUE
      M=NXH
  260 CONTINUE
      DO 270 N=1,NYH
         IF (YI.LT.YH(N)) GO TO 280
  270 CONTINUE
      N=NYH
  280 CONTINUE
      HTP=HT(M,N)
         IF (RGO(J,K).LE.SGOR) GO TO 360
      DO 290 M=1,NXH
         IF (XOI.LT.XH(M)) GO TO 300
  290 CONTINUE
      M=NXH
  300 CONTINUE
      DO 310 N=1,NYH
         IF (YOI.LT.YH(N)) GO TO 320
  310 CONTINUE
      N=NYH
  320 CONTINUE
      HTPO=HT(M,N)
C
C         THIS SECTION MOVES THE OIL AND WATER FRONTS AND ACCUMULATES
C       PRODUCTION BEFORE THE OIL FRONT REACHES A PRODUCTION WELL.
C
      VXO=0.0
      VYO=0.0
      PO=0.0
      VX=0.0
      VY=0.0
      P=0.0
      DO 330 L=1,NPIBW
      SQO=(XOI-XW(L))**2+(YOI-YW(L))**2
      PO=PO-Q(L)/HI(L)*ALOG(SQO)
      VXO=VXO+Q(L)/HI(L)*(XOI-XW(L))/SQO
      VYO=VYO+Q(L)/HI(L)*(YOI-YW(L))/SQO
      SQ=(XI-XW(L))**2+(YI-YW(L))**2
      P=P-Q(L)/HI(L)*ALOG(SQ)
      VX=VX+Q(L)/HI(L)*(XI-XW(L))/SQ
      VY=VY+Q(L)/HI(L)*(YI-YW(L))/SQ
  330 CONTINUE
      IF (PO.LT.PP(J,K)) PO=PP(J,K)
      CTY=(PP(J,K)-PI(J,K))/(((PP(J,K)-PO)/GMB+(PO-P)/OMB+(P-PI(J,K))/
```

```
     1      WMB)*GMB)
      VLX=VX/(6.2832*POR*(1-SCW-SOR-SGR))*CTY/CTR*HI(J)/HTP
      VLY=VY/(6.2832*POR*(1-SCW-SOR-SGR))*CTY/CTR*HI(J)/HTP
      VEL=SQRT(VLX**2+VLY**2)
      DT=RI/VEL
      CRF=1.0+OQ(J,K)*NSL*CTR/(Q(J)*CTY)
      VLXO=VXO/(6.2832*POR*(1-SCW-SOI-SGR))*CTY/CTR*CRF*HI(J)/HTPO
      VLYO=VYO/(6.2832*POR*(1-SCW-SOI-SGR))*CTY/CTR*CRF*HI(J)/HTPO
      VELO=SQRT(VLXO**2+VLYO**2)
      IF (VELO.GT.VEL) DT=RI/VELO
      IF (TSUMI+DT.GT.TSTOP) DT=TSTOP-TSUMI
      XI=XI+DT*VLX
      YI=YI+DT*VLY
      TSUMI=TSUMI+DT
      XOI=XOI+DT*VLXO
      YOI=YOI+DT*VLYO
C
C        CHECK IF OIL FRONT HAS REACHED A PRODUCTION WELL.
C     THE WATER FRONT IS ALSO CHECKED JUST IN CASE IT HAS GOTTEN
C     AHEAD OF THE OIL FRONT.  THIS OF COURSE IS NOT NORMAL
C     BUT CAN HAPPEN IF THE OIL PRODUCTION RATE DURING
C     FILL-UP IS TO LARGE.
C
         IF (SQRT((XI-XW(J))**2+(YI-YW(J))**2).LE.RI) GO TO 390
      CO(J,K)=CO(J,K)+DT*OQ(J,K)
      IF(VELO .LE. VLCP) GO TO 350
      IF(SQRT((XOI-XW(J))**2+(YOI-YW(J))**2).LE.RI) GO TO 348
      DO 349 LX=1,NPIBW
      IF(Q(LX) .GE. 0.0) GO TO 349
      IF(SQRT((XOI-XW(LX))**2+(YOI-YW(LX))**2).LE.RI) GO TO 348
  349 CONTINUE
C
C        WHEN THE OIL FRONT REACHES A PRODUCTION WELL THE
C     STREAMLINE GAS-OIL RATIO IS SET EQUAL TO SGOR.
C
      GO TO 350
  348 RGO(J,K)=SGOR
      NCOUNT=1
  350 CONTINUE
         IF (TSUMI.LT.TSTOP) GO TO 240
      X(J,K)=XI
      Y(J,K)=YI
      XO(J,K)=XOI
      YO(J,K)=YOI
      TSUM(J,K)=TSUMI
         GO TO 410
C
C        THIS SECTION MOVES THE WATER FRONT AND ACCUMULATES
C     THE PRODUCTION AFTER OIL FRONT BREAKTHROUGH
C
  360 CONTINUE
      VX=0.0
      VY=0.0
      P=0.0
      DO 370 L=1,NPIBW
      SQ=(XI-XW(L))**2+(YI-YW(L))**2
      P=P-Q(L)/HI(L)*ALOG(SQ)
      VX=VX+Q(L)/HI(L)*(XI-XW(L))/SQ
      VY=VY+Q(L)/HI(L)*(YI-YW(L))/SQ
  370 CONTINUE
      IF (P.LT.PP(J,K)) P=PP(J,K)
      CTY=(PP(J,K)-PI(J,K))/(((PP(J,K)-P)/OMB+(P-PI(J,K))/WMB)*GMB)
```

```
      VLX=VX/(6.2832*POR*(1-SCW-SOR-SGR))*CTY/CTR*HI(J)/HTP
      VLY=VY/(6.2832*POR*(1-SCW-SOR-SGR))*CTY/CTR*HI(J)/HTP
      VEL=SQRT(VLX**2+VLY**2)
      DT=RI/VEL
      IF (TSUMI+DT.GT.TSTOP) DT=TSTOP-TSUMI
      XI=XI+DT*VLX
      YI=YI+DT*VLY
      TSUMI=TSUMI+DT
      OQ(J,K)=-Q(J)*CTY/(CTR*NSL)
      CO(J,K)=CO(J,K)+DT*OQ(J,K)
C
C        CHECK FOR WATER FRONT BREAKTHROUGH
C
         IF (SQRT((XI-XW(J))**2+(YI-YW(J))**2).LE.RI) GO TO 390
  380 CONTINUE
         IF (TSUMI.LT.TSTOP) GO TO 240
      X(J,K)=XI
      Y(J,K)=YI
      TSUM(J,K)=TSUMI
      XO(J,K)=XOI
      YO(J,K)=YOI
         GO TO 410
  390 CONTINUE
C
C        THIS SECTION IS USED WHEN THE WATER FRONT FIRST
C      BREAKS THROUGH.
C
      RGO(J,K)=SGOR
      CTY=WMB/GMB
      WQ(J,K)=-Q(J)*CTY/(NSL*CTR)
      OQ(J,K)=0.0
      X(J,K)=XI
      Y(J,K)=YI
      TSUM(J,K)=TSUMI
      XO(J,K)=XOI
      YO(J,K)=YOI
      CW(J,K)=(TSTOP-TSUMI)*WQ(J,K)
         GO TO 410
  400 CONTINUE
C
C      ACCUMULATE PRODUCTION AFTER WATER BREAKTHROUGH
C
      CTY=WMB/GMB
      WQ(J,K)=-Q(J)*CTY/(NSL*CTR)
      CW(J,K)=CW(J,K)+DELT*WQ(J,K)
  410 SMCTY=SMCTY+CTY
  420 CONTINUE
      CTR=SMCTY/NTSL
         IF (TSTOP.LT.TSMP) GO TO 450
C
C        AT SPECIFIED TIME INTERVALS
C      ALL STREAMLINES ARE SUMMED AND RESULTS ARE PRINTED
C      FOR EACH WELL AND FOR THE ENTIRE FIELD.
C      PLOTS ARE MADE OF THE OIL FRONT AND WATER FRONT POSITIONS.
C
      ORT=0.0
      WRT=0.0
      SOIL=0.0
      SWAT=0.0
      DO 440 J=1,NPIW
         IF (Q(J).GE.0.0) GO TO 440
      GR=0.0
```

```
      OR=0.0
      WR=0.0
      OPRD=0.0
      WPRD=0.0
      NSL=-NST*Q(J)/QMNP+0.5
      DO 430 K=1,NSL
      OPRD=OPRD+CO(J,K)/158990.
      WPRD=WPRD+CW(J,K)/158990.
      GR=GR+RGO(J,K)*OQ(J,K)/1.8401
      OR=OR+OQ(J,K)/1.8401
      WR=WR+WQ(J,K)/1.8401
  430 CONTINUE
      GSR=GR/OR
      WOR=WR/OR
      EX=XW(J)/30.48
      WY=YW(J)/30.48
      PRINT 620, J,EX,WY
      PRINT 630, GR,OR,WR
      PRINT 640, OPRD,WPRD,GSR,WOR
      ORT=ORT+OR
      WRT=WRT+WR
      SOIL=SOIL+OPRD
      SWAT=SWAT+WPRD
  440 CONTINUE
      TMEI=TSTOP/86400.0
      PRINT 650, ORT,WRT
      PRINT 651, SOIL,SWAT
      PRINT 660, TMEI,CTR
C
C        MAXIMUM PLOT LENGTH IS 11 FT.
C     PLOT LENGTH IS ESTIMATED AND IF IT IS GREATER THAN
C     11 FT, THE PLOTTING IS STOPPED.
C
      IF((11.0-TOTFT) .LT. PLTFT) GO TO 441
      TOTFT=TOTFT+PLTFT
      CALL OBPLT
  441 CONTINUE
      TSMP=TSMP+DELP
  450 CONTINUE
C
C        INCREMENT TIME TO NEXT STOPPING POINT.
C     IF TIME IS GREATER THAN TMX - STOP CALCULATIONS.
C     IF OIL FRONT HAS BROKEN THROUGH IN AT LEAST ONE STREAMLINE
C     ,NCOUNT=1,SET DELT = DELT*10.
C
        IF(NCOUNT.EQ.1) DELT=DELTT
       TSTOP=TSTOP+DELT
        IF (TSTOP.GT.TMX) GO TO 460
        GO TO 230
  460 CONTINUE
      CALL ENDPLT
  470 CONTINUE
  480 FORMAT  (//,8X,*NP = *,I3,*  NI = *,I3,*  NBW = *,I3,*  NBP = *,I3
     1,*  NST = *,I3)
  490 FORMAT  (//,8X,*H = *,F10.5,*  DELT = *,F10.5,*  TMX = *,F10.1,*
     1RI = *,F10.5)
  500 FORMAT  (//,8X,*DELP = *,F10.5,*  XMX = *,F10.1,*  YMX = *,F10.1,
     1 *  QMNP = *,F10.5)
  510 FORMAT  (//,8X,*POR = *,F6.5,*  SCW = *,F6.5,*  SOI = *,F6.5,*  SO
     1R = *,F6.5,*  SGR = *,F6.5)
  520 FORMAT  (//,8X,*OIL MOB = *,F10.5,*  WAT MOB = *,F10.5,*  GAS MOB
     1= *,F10.5)
```

```
530   FORMAT  (6F10.0)
540   FORMAT  (6I10)
550   FORMAT  (6F10.2)
560   FORMAT  (2F10.0)
570   FORMAT  (*NO OIL BANK WILL FORM BECAUSE THE INITIAL OIL SATURATION
     1 IS NOT GREATER THAN THE RESIDUAL OIL SATURATION.*)
580   FORMAT  (12F5.0)
590   FORMAT (1H1)
595   FORMAT  (8X,*INTERVAL WELL BALANCE DEFEATED*)
600   FORMAT  (8X,*BOUNDING COMPLETE*)
610   FORMAT  (8X,*RUNBACK COMPLETE*)
620   FORMAT (//,5X,*WELL NO *,I2,* AT *,E10.3,* ,*,E10.3,*.*)
630   FORMAT  (/,10X,*GAS RATE = *,E10.3,*. OIL RATE = *,F8.2,*. WATER R
     1ATE = *,F8.2,*.*)
640   FORMAT (/,10X,*CUM OIL = *,E10.3,*. CUM WAT = *,E10.3,*, GOR = *,
     1 E10.3,* . WOR = *,E10.3)
650   FORMAT (/15X,*FIELD OIL RATE = *,E10.3,*, WATER RATE = *,E10.3)
651   FORMAT (/15X,*FIELD CUM OIL = *,E10.3,*, FIELD CUM WATER = *,
     1E10.3)
660   FORMAT (/15X,*TIME = *,E10.3,*DAYS. CONDUCTIVITY RATIO = *,E10.3
     1 *.*,///)
      END
C
C          SUBROUTINE TO BOUND IRREGULAR RESERVOIRS
C        REF: J.-K. LIN, PH.D. DISSERTATION, THE UNIVERSITY OF
C             TEXAS AT AUSTIN (DECEMBER,1972).
C
      SUBROUTINE BOUND
      COMMON/AAA/ XW(125),YW(125),HI(125),Q(125),XB(125),
     1YB(125),NBP,NP,NI,NBW,H
      COMMON/BBB/ C(55,55),D(55),QI(55)
      DIMENSION XI(55),YI(55),XSB(100),YSB(100),XIB(100),
     1YIB(100),AA(100,55),BB(100),DS(100)
      NBP1=NBP+1
      PAI=3.14159
      L=NP+NI
      DO 10 J=1,NBW
      XI(J)=XW(J+L)
      YI(J)=YW(J+L)
10    CONTINUE
      XB(NBP1)=XB(1)
      YB(NBP1)=YB(1)
      CC=0.5
      DO 20 I=1,NBP
      XM=0.5*(XB(I+1)+XB(I))
      YM=0.5*(YB(I+1)+YB(I))
      DS(I)=SQRT((XB(I+1)-XB(I))**2+(YB(I+1)-YB(I))**2)
      HDS=CC*DS(I)
      TN=YB(I+1)-YB(I)
      TD=XB(I+1)-XB(I)
      THETA=ATAN2(TN,TD)
      BETA=THETA-0.5*PAI
      XIB(I)=XM+HDS*COS(BETA)
      XSB(I)=XM+HDS*COS(BETA+PAI)
      YIB(I)=YM+HDS*SIN(BETA)
      YSB(I)=YM+HDS*SIN(BETA+PAI)
20    CONTINUE
      N=NBW
      M=NBP
      DO 30 I=1,NBP
      DO 30 J=1,NBW
      FNUM=(XSB(I)-XI(J))**2+(YSB(I)-YI(J))**2
```

```
      FDEN=(XIB(I)-XI(J))**2+(YIB(I)-YI(J))**2
      FACT=FNUM/FDEN
      AA(I,J)=ALOG(FACT)
   30 CONTINUE
      DO 50 J=1,NBP
      SUM=0.0
      DO 40 K=1,L
      FN=(XIB(J)-XW(K))**2+(YIB(J)-YW(K))**2
      FD=(XSB(J)-XW(K))**2+(YSB(J)-YW(K))**2
      DSUM=Q(K)/HI(K)*ALOG(FN/FD)
      SUM=SUM+DSUM
   40 CONTINUE
      BB(J)=SUM
   50 CONTINUE
      DO 70 I=1,N
      DO 70 K=1,I
      C(K,I)=0.0
      DO 60 J=1,M
      C(K,I)=C(K,I)+AA(J,I)*AA(J,K)
   60 CONTINUE
      C(I,K)=C(K,I)
   70 CONTINUE
      DO 80 I=1,N
      D(I)=0.0
      DO 80 J=1,M
      D(I)=D(I)+BB(J)*AA(J,I)
   80 CONTINUE
      CALL SOLVE(N)
      DO 90 J=1,NBW
      Q(J+L)=QI(J)*H
   90 CONTINUE
      RETURN
      END
C
C         SUBROUTINE SOLVE USED BY SUBROUTINE BOUND , SEE BOUND
C       FOR REFERENCE.
C
      SUBROUTINE SOLVE(N)
      COMMON/BBB/ C(55,55),D(55),QI(55)
      DIMENSION A(55,55),ID(55)
      NN=N+1
      M=N
      DO 10 I=1,M
      A(I,NN)=D(I)
      ID(I)=I
      DO 10 J=1,N
      A(I,J)=C(I,J)
   10 CONTINUE
      K=1
   20 CONTINUE
      NR=K
      NC=K
      B=ABS(A(K,K))
      DO 40 I=K,M
      DO 40 J=K,N
         IF (ABS(A(I,J))-B) 40,40,30
   30 CONTINUE
      NR=I
      NC=J
      B=ABS(A(I,J))
   40 CONTINUE
         IF (NR-K) 70,70,50
```

```
50    CONTINUE
      DO 60 J=K,NN
      C=A(NR,J)
      A(NR,J)=A(K,J)
      A(K,J)=C
60    CONTINUE
70    CONTINUE
         IF (NC-K) 100,100,80
80    CONTINUE
      DO 90 I=1,M
      C=A(I,NC)
      A(I,NC)=A(I,K)
      A(I,K)=C
90    CONTINUE
      I=ID(NC)
      ID(NC)=ID(K)
      ID(K)=I
100   CONTINUE
110   CONTINUE
         IF (A(K,K)) 120,180,120
120   CONTINUE
      KK=K+1
      DO 140 J=KK,NN
      A(K,J)=A(K,J)/A(K,K)
      DO 140 I=1,M
         IF (K-I) 130,140,130
130   CONTINUE
      A(I,J)=A(I,J)-A(I,K)*A(K,J)
140   CONTINUE
      K=KK
         IF (K-N) 20,110,150
150   CONTINUE
      DO 170 I=1,N
      DO 170 J=1,N
         IF (ID(J)-I) 170,160,170
160   CONTINUE
      QI(I)=A(J,NN)
170   CONTINUE
         GO TO 190
180   CONTINUE
      PRINT 200
190   CONTINUE
      RETURN
200   FORMAT  (19H NO UNIQUE SOLUTION )
      END
C
C          THIS SUBROUTINE PLOTS THE LOCATIONS OF THE OIL AND
C       WATER FRONTS AS THEY DEVELOPE.  ALL DATA IS TAKEN FROM
C       THE MAIN PROGRAM.
C
      SUBROUTINE OBPLT
      COMMON/AAA/ XW(125),YW(125),HI(125),Q(125),XB(125),
     1YB(125),NBP,NP,NI,NBW,H
      COMMON/CCC/ X(80,20),Y(80,20),XO(80,20),YO(80,20),
     1WQ(80,20),SCL,XMX,YMX,NST,QMNP,RGO(80,20),
     2SGOR,NPIW,TMEI
      CALL SYMBOL (0.5,10.5,.14,7HTIME = ,270.0,7)
      CALL NUMBER (999.0,999.0,.14,TMEI,270.0,0)
      CALL SYMBOL (999.0,999.0,.14,5H DAYS,270.0,5)
      CALL PLT (1.125*XMX*SCL,1.125*YMX*SCL,-3)
      CALL PLT (XB(NBP)*SCL,YB(NBP)*SCL,3)
      DO 10 I=1,NBP
```

```
      CALL PLT (XB(I)*SCL,YB(I)*SCL,2)
10    CONTINUE
      DO 30 I=1,NPIW
         IF (Q(I).GE.0.0) GO TO 20
      CALL SYMBOL (XW(I)*SCL,YW(I)*SCL,.07,1,0,-1)
         GO TO 30
20    CONTINUE
      CALL SYMBOL (XW(I)*SCL,YW(I)*SCL,.07,7,0,-1)
30    CONTINUE
      DO 50 J=1,NPIW
         IF (Q(J).GE.0.0) GO TO 50
      NSL=-NST*Q(J)/QMNP+0.5
      DO 50 K=1,NSL
         IF (ABS(XO(J,K)).GT.XMX) GO TO 40
         IF (ABS(YO(J,K)).GT.YMX) GO TO 40
         IF (RGO(J,K).LE.SGOR) GO TO 40
      CALL SYMBOL (XO(J,K)*SCL,YO(J,K)*SCL,.07,31,0,-1)
40    CONTINUE
         IF (ABS(X(J,K)).GT.XMX) GO TO 50
         IF (ABS(Y(J,K)).GT.YMX) GO TO 50
         IF (WQ(J,K).GT.0.0) GO TO 50
      CALL SYMBOL (X(J,K)*SCL,Y(J,K)*SCL,.07,40,0,-1)
50    CONTINUE
      CALL PLT (0.0,0.0,999)
      RETURN
      END
```

.175	.35	.60	.20	0.0	50.
	4	4	40	58	7
	6	3			
48.	30.	25.	500.	4000.	46.
.74	4000.	4000.	50.	.75	2.9
500.	300.	50.	-50.	3.	1000.
710.	-340.	50.	41.		
-300.	700.	50.	-50.	3.	1000.
-100.	100.	48.	81.		
90.	-560.	50.	-50.	3.	1000.
-920.	490.	50.	40.		
-700.	-120.	46.	-46.	3.	1000.
-520.	-760.	46.	34.		
3000.	1500.				
2500.	1700.				
2000.	1500.				
1500.	1700.				
1000.	1500.				
500.	1700.				
0.0	1500.				
-500.	1700.				
-1000.	1500.				
-1500.	1700.				
-2000.	1500.				
-2300.	1550.				
-2500.	1300.				
-2800.	1350.				
-2900.	1100.				
-3200.	900.				
-3000.	600.				
-3200.	300.				
-3000.	0.0				
-3200.	-500.				
-3000.	-1000.				
-3200.	-1500.				
-3000.	-2000.				
-2750.	-2250.				
-2500.	-2500.				
-2150.	-2600.				
-1800.	-2500.				
-1400.	-2600.				
-1000.	-2300.				
-500.	-2100.				
0.0	-1700.				
500.	-1350.				
1000.	-1000.				
1600.	-700.				
2000.	-300.				
2500.	100.				
3000.	500.				
3200.	800.				
3400.	1100.				
3200.	1300.				
2800.	1000.				
2650.	1000.				
2500.	1000.				
2250.	1000.				
2000.	1000.				
1750.	1000.				
1500.	1000.				
1250.	1000.				

```
1000.     1000.
750.      1000.
500.      1000.
250.      1000.
0.0       1000.
-250.     1000.
-500.     1000.
-750.     1000.
-1000.    1000.
-1250.    1000.
-1500.    1000.
-1750.    1000.
-2000.    1000.
-2250.    1000.
-2400.    900.
-2500.    750.
-2500.    500.
-2500.    250.
-2500.    0.0
-2500.    -250.
-2500.    -500.
-2500.    -750.
-2500.    -1000.
-2500.    -1250.
-2500.    -1500.
-2500.    -1750.
-2400.    -1900.
-2250.    -2000.
-2000.    -2000.
-1750.    -2000.
-1500.    -2000.
-1250.    -1950.
-1000.    -1900.
-750.     -1700.
-500.     -1500.
-250.     -1350.
0.0       -1200.
250.      -1000.
500.      -800.
750.      -650.
1000.     -500.
1250.     -300.
1500.     -100.
1750.     100.
2000.     300.
2150.     400.
2300.     500.
2500.     650.
2700.     800.
2750.     900.
40.  42.  48.
42.  44.  49.
46.  46.  49.
50.  50.  50.
50.  50.  50.
50.  50.  50.
-2000-10000.0  1000.2000.3000.
-10000.0  1000.
```

BIBLIOGRAPHY

1. U. S. Department of the Interior, Geological Survey, Professional Paper 163, The Significance of Geologic Conditions in Naval Petroleum Reserve No. 3, Wyoming, 1931.

2. LeBlanc, J. C., and Caudle, B. H., "A Streamline Model for Secondary Recovery", Soc. Pet. Engr. (1971), II, 7.

3. Rust, C. B., A Streamline Simulator for Oil Bank Buildup in a Waterflood, M.S. Thesis, The University of Texas at Austin (May, 1972), Report No. UT-72-4, Texas Petroleum Research Committee (May, 1972).

4. Wessels, J. W., Application of the Streamline Reservoir Model to Reservoirs Having Variations in Formation Thickness, M. S. Thesis, The University of Texas at Austin (May, 1973), Report No. UT-73-1, Texas Petroleum Research Committee (May, 1973).

5. Kazmann, W. M., Application of the Streamline Reservoir Model to the Design of Waterflood Projects, M. S. Thesis, The Univeristy of Texas at Austin (December, 1974).

6. Caudle, B. H., Fundamentals of Reservoir Engineering, Soc. Pet. Engr. of AIME, Dallas, Texas, 1967.

7. Lin, J.-K., An Image Well Method for Bounding Arbitrary Reservoir Shapes in the Streamline Model, Ph.D. Dissertation, The University of Texas at Austin (December, 1972).

8. "Character of Second Wall Creek Production", Plate VII, Tesoro Petroleum Corporation, San Antonio, Texas (April, 1970).

9. History of Naval Petroleum and Oil Shale Reserves, Office of Naval Petroleum and Oil Shale Reserves, Department of the Navy, Washington, D. C. (1 October 1973).

10. "Isopachous Map of the Second Wall Creek Sand", Plate IV, Tesoro Petroleum Corporation, San Antonio, Texas (6 December 1972).

11. "Proposed Final Development—Teapot Dome Oilfield Naval Petroleum Reserve 3", U. S. Navy Drawing (April 15, 1970).

12. Officer in Charge, Naval Petroleum and Oil Shale Reserves in Colorado, Utah and Wyoming, letter, Serial No. 41-65, 18 March 1965.

13. Officer in Charge, Naval Petroleum and Oil Shale Reserves in Colorado, Utah and Wyoming, letter, Serial No. 52-65, 30 March 1965.

VITA

Kenneth Earl Goltz was born in Cleveland, Ohio on August 28, 1945, the son of Eleanor Louise Goltz and Leonard Henry Goltz. After completing his work at North Olmsted High School, North Olmsted, Ohio, in 1963, he entered Fenn College (now The Cleveland State University) in Cleveland, Ohio. He received the degree of Bachelor of Chemical Engineering from The Cleveland State University in May, 1968. For the next year he worked as a production foreman with the B. F. Goodrich Chemical Company, Avon Lake, Ohio.

On August 22, 1969, he was commissioned as an Ensign in the United States Navy Civil Engineer Corps. After attending the Civil Engineer Corps Officer School at Port Hueneme, California he was assigned to the Navy Public Works Center, Yokosuka, Japan and most recently to Commander Fleet Activities, Sasebo, Japan as the Assistant Public Works Officer.

He was selected for postgraduate education in Petroleum Engineering and entered the Graduate School of The University of Texas in June, 1974.

Kenneth married Diane Christine Grzybowicz of North Olmsted, Ohio on May 28, 1966. They have a son, Stephen Kenneth, born March 31, 1975.

Permanent Address: 24855 Maple Ridge Rd.
North Olmsted, Ohio 44070

This thesis was typed by Dorothy Watson.

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